A STUDY OF METAL FLOW DURING INTEGRAL END CLOSURE EXTRUSION CLADDING

William Wegner

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by

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A STUDY OF METAL FLOW DURING

INTERNAL HIGH ENERGY-RATE FORMING

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A STUDY OF METAL FLOW DURING INTEGRAL END CLOSURE EXTRUSION CLADDING

by

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Submitted to the Department of Chemical Engineering, Massachusetts Institute of Technology, in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Lead and lead-antimony alloys of three various stiffnesses were co-extruded through a circular die at area reduction ratios of 4, 9, 16, and 25. The interface between the two cylindrical billets was made in the shape of a cone with various preset apex angles of 180°, 170°, 160° and 150°. This comprised a set of 144 different test samples that were extruded by the direct process in order to study the effects of the above mentioned variables. These experiments were carried out at constant conditions of die geometry, lubrication, room temperature, and ram speed.

The results showed that for a particular ratio of stiffnesses between the billets (K_1/K_2) and a given cone angle, as the extrusion ratio was increased the interface distortion increased. Also, other conditions being fixed, as K_1/K_2 increases, the interface distortion, if plotted in the form of a defect area, will result in an S-shaped curve which has a maximum and minimum which are reached somewhere in the neighborhood where the stiffness of the first metal out is slightly greater than that which follows.

It was also found that when K_1/K_2 was small (about 0.5) voids would form between the extruded billets.

The variation of the apex cone angle showed that, in general, if the cone angle was decreased the size of the interface distortion decreased. This decrease continued to a certain point and then the interface would reverse itself and increase in the opposite direction. This situation was not studied since the lowest cone angle used was 150°.

A STUDY OF AXIAL FLOW TURBINE
INTERNAL AND CLOSURE ARRANGEMENT CLEARANCE

by

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Submitted to the Department of Chemical Engineering, Massachusetts Institute of Technology, in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Lead and lead-antimony alloys of three various stiffnesses were co-extruded through a circular die at area reduction ratios of 4, 7, 10, and 25. The interface between the two cylindrical billets was made in the shape of a cone with various apex angles of 180°, 170°, 160° and 150°. This comprised a set of 12 different test samples that were extruded by the direct process in order to study the effects of the above mentioned variables. These experiments were carried out at constant conditions of die geometry, lubrication, room temperature, and ram speed.

The results showed that for a particular ratio of stiffnesses between the billets (E_1/E_2) and a given cone angle, as the extrusion ratio was increased the interface distortion decreased. Also, under conditions being fixed, as K_1/K_2 increased, the interface distortion, if plotted in the form of a direct sine, will result in an S-shaped curve which has a maximum and minimum which are reached somewhere in the neighborhood where the stiffness of the first metal may be slightly greater than that which follows.

It was also found that when E_1/E_2 was small (about 0.4) voids would form between the extruded billets.

The variation of the apex cone angle showed that, in general, if the cone angle was decreased the size of the interface distortion decreased. This decrease continued to a certain point and then the interface would reverse itself and increase in the opposite direction. This extremities was not attained since the lowest cone angle used was 150°.

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I. INTRODUCTION

In the process of manufacturing fuel elements for reactors it is necessary to clad the nuclear fuel with a more corrosion resistant metal so that the fuel elements can be subjected to the flow of the heat-dissipating medium and also be capable of withstanding shock. One method of doing this in the case of cylindrical fuel elements has been to co-extrude the fuel material along with the cladding metal. This is normally done by "canning" the fuel material prior to extrusion. Dimensions are chosen so that after extrusion the proper thickness of clad is obtained. This, in itself, presents no great difficulty, and is accomplished with extreme accuracy. However, since these elements are of finite length and must be extruded as such, difficulty arises at the ends where the clad material faces on to the fuel material. Instead of getting a flat interface between the two metals, as one would like to have, the normal result is an irregularly shaped interface.

Typical of all extrusions is a phenomenon which is called an "extrusion defect", or just the "defect". As in the flow of fluids, once a steady state condition is reached and no discontinuities are introduced the flow pattern remains constant. Such would be the case with extrusions if only one stiffness of metal were used; but in the case of co-extrusion, at least two different stiffnesses of metal are used.

In order to illustrate the significance of the "defect", consider a single metal being extruded through a die in which a grid has been superimposed on a center plane as in Figure 1.

As force is applied to the piston, a point will be reached when the shear stress is greater than the shear modulus of the metal and flow will

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commence. The first squares of the orthogonal grid will be distorted to a new shape and successive squares will result in varying shapes until a steady state condition is reached. This steady state condition is shown in Figure 2.

Finally, as the last of the metal approaches the die, the pattern changes again and neither resembles the initial pattern nor the steady state pattern. These variations of grid pattern at the beginning and end of the extrusion as compared to the steady flow pattern are examples of "defects". Some authors refer to the distortion of the orthogonal grid pattern as a "defect", but this experimenter will use the term "grid distortion" for this in order to differentiate between the two. In other words, every element of an extrusion undergoes grid distortion, whereas the defect occurs only at discontinuities.

Imagine now, two materials of different stiffnesses arranged as in Figure 3 being extruded through the same arrangement as before.

Depending upon the relative stiffnesses and many other variables, the result will, in general, be as is shown in Figure 4.

The fact that the interface between the two dissimilar materials is no longer a straight line and can extend for great lengths is the problem to be attacked by this paper.

Were it possible to weld or somehow cap the ends of extrusions, the defect would present no problem because one long extrusion could be made, cut into desired lengths, and capped. Due to the nature of the metals concerned and to the desirability of a metallic bond at the end between the meat and the clad this is not possible at the present time and consequently some means had to be developed to eliminate or reduce the defect.

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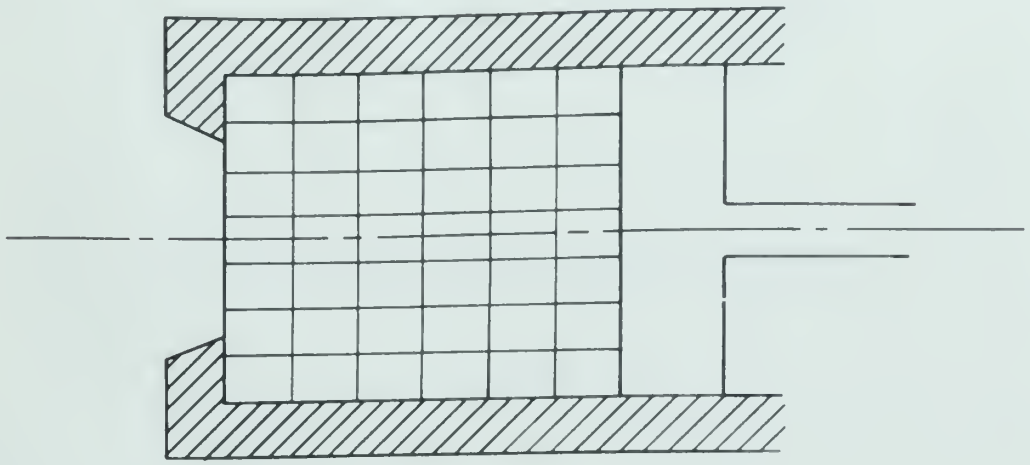

FIGURE 1

Direct Extrusion Process Showing Orthogonal Grid Lines Prior to Extrusion

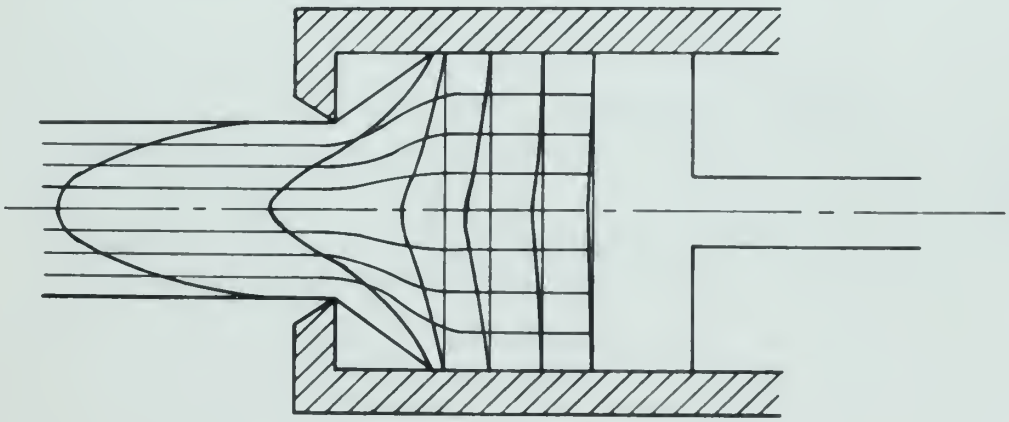

FIGURE 2

Direct Extrusion Process Showing Grid Lines After Extrusion

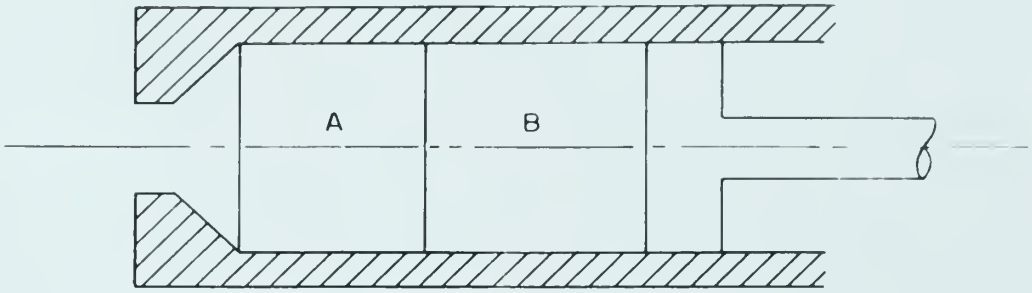

FIGURE 3

Extrusion Billet Consisting of Two Dissimilar Metals (A and B) Prior to Extrusion

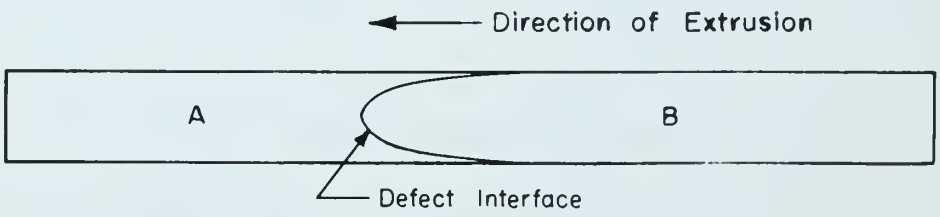

FIGURE 4

Extrusion Billet After Extrusion Showing Interface Between Two Dissimilar Metals

Presently this is done by preshaping the interface so that a straight interface is approached in the final result. The exact geometry of the preshape is arrived at by experimental methods for each particular case and can be called nothing more than a trial-and-error method. It will be the object of this paper to investigate systematically the formation of the defect.

Since the main problem in this investigation centered around the behaviors of two metals having different stiffnesses, the first problem was to arrive at an experiment which would show the effects of this property. In the beginning, the idea of using a commercial plastic clay called "Plasticine" was tried and many experiments were carried out with this material. Plasticine had possible advantages in that different stiffnesses might be easily attained by merely adding given amounts of talc and kneading the clay until it was homogeneous. Also there was quite a large background of material available where Plasticine had been used to study the flow of metal during extrusions, rolling and etc. Also in its favor was its relative ease of fabrication, its ability to be made in various colors, and its extremely low extrusion pressure.

Its disadvantages lie in the fact that its properties are so dependent upon temperature that a few degrees' change will alter its characteristics noticeably. Another difficulty encountered was dimensional stability of the billets prior to extrusion. Since the whole investigation centered around the interface, it was mandatory that the original billet interface be quite exact and very reproducible for hundreds of extrusions. The very softness of the Plasticine prevented this stability to any great degree but it is felt that this problem could

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this material. Plasticine had possible advantages in that different
called "Plasticine" was tried and many experiments were carried out with
property. In the beginning, the idea of using a commercial plastic clay
was to arrive at an experiment which would show the effects of this
behaviors of two metals having different skillfulness, the first problem

Since the main problem in this investigation centered around the
the object of this paper to investigate systematically the formation of
the defect.

preshape is arrived at by experimental methods for each particular case
and can be called nothing more than a trial-and-error method. It will be
interface is approached in the final result. The exact geometry of the

Presently this is done by preshaping the interface so that a straight

have been solved by lowering the temperature of the Plasticine during the making of the billet in order to make it easier to maintain tolerances.

Appendix B details some of the experiments carried out with Plasticine prior to the time that a new material was selected.

In the selection of the new material certain qualities were predominant: (1) it should be a metal, (2) it should be relatively soft so that the testing equipment available could be used, (3) it must be possible to vary its stiffness but not change its over-all characteristics, and (4) it should be a material which is readily available and safe to use. After looking over the field it was decided that lead fulfilled the specifications since antimony could be added in small percentages to increase its hardness.

The only objection to this selection was the fact that at room temperature lead and antimony would not form a solid solution and the possibility existed of having variations in the metal due to non-homogeneity. In order to find out if this problem was of sufficient magnitude to exclude the use of these two metals, a test was made by extruding a long billet containing 10 percent antimony and testing each piece of this billet by extruding through another die to determine if its properties changed with respect to position in the originally cast billet. No differences were noted so it was tacitly assumed that all cast billets were homogeneous.

By calling local lead distributors it was learned that lead containing any desired amounts of antimony was obtainable by order, but that 3 percent and 10 percent were readily available and required no special procurement. Pure lead (99.99 percent) was also available as a

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melting of the billet in order to make it easier to maintain tolerances. have been solved by lowering the temperature of the plasticine during the

standard stock item. Thus, the selection was made to use three different types of lead: pure, 3 percent antimony, and 10 percent antimony.

Having selected the material to be used, the next step was to determine the experiment which would enable an investigation concerning the extrusion interface to be studied.

II. THE EXPERIMENT

Since most of the extrusions made in general practice are of the direct extrusion type, it was decided that this experiment would also use the direct process. Figure 1 is an example of the direct extrusion process. The simplest geometry for extrusion is the cylindrical type where the cross-sections of the billet and of the extrusion are circles. This type of geometry was selected.

The next selection was the size of the billets and the extrusion. The determining factor here was the apparatus available which is described in Chapter III. A few simple calculations showed that a 3/4-inch diameter billet could be extruded through a 25 to 1 reduction ratio and from this limiting arrangement the billet size was fixed at .748-inch diameter (.002-inch under the .750-inch value so that the billet would fit into a .750-inch diameter cylinder). Four different values of reduction ratio were selected:

(1) 4 to 1
(2) 9 to 1
(3) 16 to 1
(4) 25 to 1

It was felt that this range would cover the possible range now being used for extrusions and would yield sufficient data to investigate the problem. Thus, at this point there are three different materials and four different extrusion ratios, resulting in a possibility of twelve different conditions. If it is now allowed to use two different billets in the cylinder instead of one, and also specify the material which is first extruded, the possibilities are tripled and thirty-six combinations are available.

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The introduction of one more variable now completes the necessary variations which are required: that of preshaping the interface of the billet. In order to understand why the particular shapes were chosen, it is necessary to explain some profound results obtained in the Plasticine experiments.

After working with Plasticine for several weeks trying to obtain a flat interface by preshaping the billets, the idea came to this investigator of double extrusion. In this process a billet consisting of two materials having a flat interface was extruded at an extrusion ratio roughly the square root of the final extrusion ratio required. See Figure 5. This resulted in a billet having an extrusion defect as shown in Figure 6. It was now proposed to re-extrude this billet, but in the opposite direction, so that the final extrusion would again contain a flat interface as in Figure 5. The idea was to let the physical properties of the metal and the extrusion determine the complicated preshaping of the billet so as to result in a flat interface.

This experiment was performed many times and always resulted in the confusing and then-unexplainable situation of an extrusion defect much larger and in the <u>opposite</u> direction of the final extrusion. In other words, the billet in Figure 7 was extruded in the direction shown, resulting in Figure 8. Then the billet in Figure 8 was extruded in the direction shown in Figure 9, and resulted in Figure 10. Theory available could not explain this result. At first it was felt that the Plasticine was the reason for this difficulty, so an experiment was carried out using aluminum and the same result was obtained. See Appendix C.

Careful analysis and precise evaluation shows that the result obtained could be predicted if one realizes that there is some angle in

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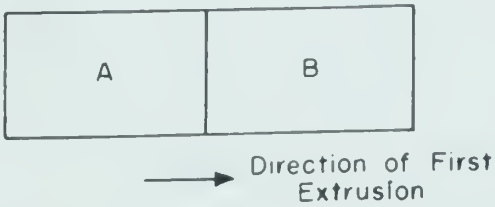

FIGURE 5

Billet Arrangement for First Extrusion in a Double Extrusion Process

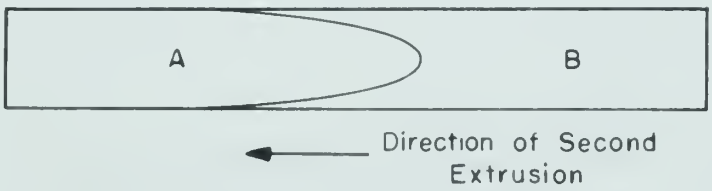

FIGURE 6

Billet Arrangement for Second Extrusion in a Double Extrusion Process

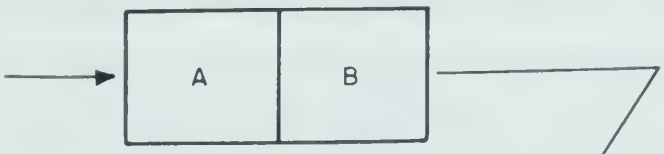

FIGURE 7

FIGURE 8

FIGURE 9

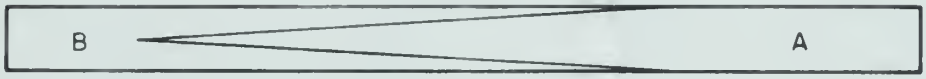

FIGURE 10

Figures Showing Results Obtained with Double Extrusion when Extrusion Ratios of First and Second Extrusions are Equal.

the preshaped interface, after which the first extrusion defect will not reverse itself, but will indeed increase in defect length. An analysis based on preservation of volume shows this angle to be around 15° for all materials and will be discussed in detail later on.

Having arrived at this angle of 15° for preshaping, it was decided to investigate four different angles in the lead experiment, namely:

(1) 0°

(2) 5°

(3) 10°

(4) 15°

Figure 11 shows the general shape of the billet with the cone-shaped interface. With these four new combinations available the final combinations rose to 144, which was the final number of experiments as actually performed. Table I gives a schedule of these different experiments. No two of these extrusions were the same.

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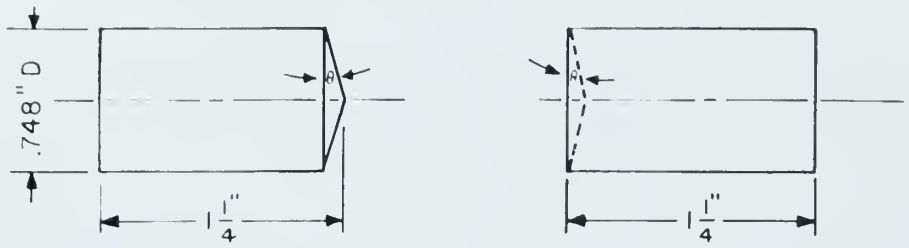

$\theta = 0°, 5°, 10°, 15°$

Material Lead (Pure, 3% & 10% Antimony)

FIGURE 11

Extrusion Billet

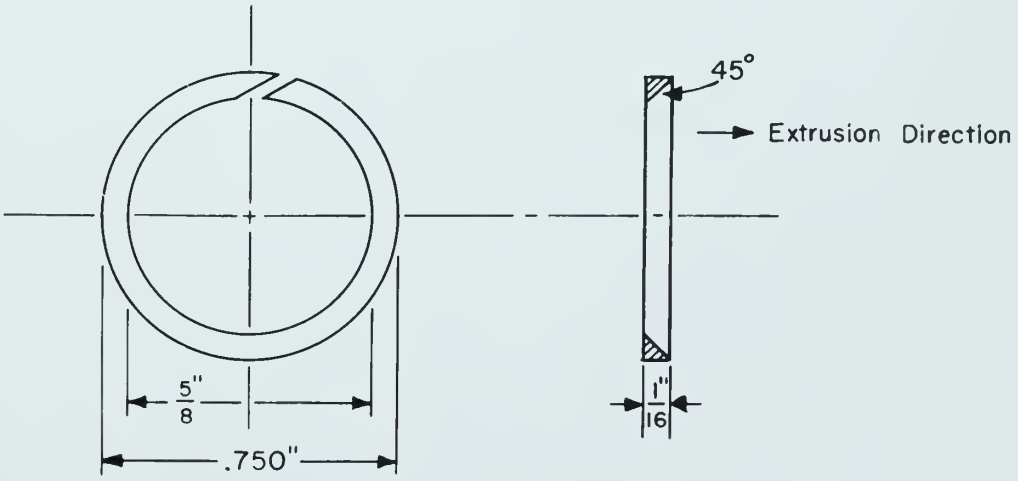

FIGURE 13

Split-Ring for Preventing Flashing

TABLE I

θ	EXTRUSION RATIO A_1/A_2			
	4	9	16	25
0°	P→P #1	P→P #10	P→P #19	P→P #28
	3→3 #5	3→3 #11	3→3 #20	3→3 #29
	10→10 #2	10→10 #12	10→10 #21	10→10 #30
	P→3 #6	P→3 #13	P→3 #22	P→3 #31
	P→10 #4	P→10 #14	P→10 #23	P→10 #32
	3→P #7	3→P #15	3→P #24	3→P #33
	3→10 #8	3→10 #16	3→10 #25	3→10 #34
	10→P #3	10→P #17	10→P #26	10→P #35
	10→3 #9	10→3 #18	10→3 #27	10→3 #36
5°	P→P #37	P→P #91	P→P #100	P→P #109
	3→3 #38	3→3 #92	3→3 #101	3→3 #110
	10→10 #39	10→10 #93	10→10 #102	10→10 #111
	P→3 #40	P→3 #94	P→3 #103	P→3 #112
	P→10 #41	P→10 #95	P→10 #104	P→10 #113
	3→P #42	3→P #96	3→P #105	3→P #114
	3→10 #43	3→10 #97	3→10 #106	3→10 #115
	10→P #44	10→P #98	10→P #107	10→P #116
	10→3 #45	10→3 #99	10→3 #108	10→3 #117

TABLE I (Continued)

	4	9	16	25
10°	P→P #46	P→P #118	P→P #127	P→P #136
	3→3 #47	3→3 #119	3→3 #128	3→3 #137
	10→10 #48	10→10 #120	10→10 #129	10→10 #138
	P→3 #49	P→3 #121	P→3 #130	P→3 #139
	P→10 #50	P→10 #122	P→10 #131	P→10 #140
	3→P #51	3→P #123	3→P #132	3→P #141
	3→10 #52	3→10 #124	3→10 #133	3→10 #142
	10→P #53	10→P #125	10→P #134	10→P #143
	10→3 #54	10→3 #126	10→3 #135	10→3 #144
15°	P→P #55	P→P #64	P→P #73	P→P #82
	3→3 #56	3→3 #65	3→3 #74	3→3 #83
	10→10 #57	10→10 #66	10→10 #75	10→10 #84
	P→3 #58	P→3 #67	P→3 #76	P→3 #85
	P→10 #59	P→10 #68	P→10 #77	P→10 #86
	3→P #60	3→P #69	3→P #78	3→P #87
	3→10 #61	3→10 #70	3→10 #79	3→10 #88
	10→P #62	10→P #71	10→P #80	10→P #89
	10→3 #63	10→3 #72	10→3 #81	10→3 #90

III. THE APPARATUS

A 20,000-pound Tinius-Olsen Testing Machine was used to provide the power for the extrusions. Means were available on this machine to accurately set the speed of the cross-head which, in effect, was the ram-speed of the extrusion. Since the extrusion pressure is greatly dependent upon the ram-speed, it was decided that the ram-speed would be held constant for all the extrusions and was ultimately set at one inch per minute.

This machine also provided means for recording the load versus ram travel graphically and these graphs were used to obtain a permanent record throughout the entire run of the extrusion. An example of one of these records is presented in Figure 14.

The actual extrusion apparatus was made as simple as possible and consisted of a cylinder, ram, dies, and stand. Plans of these are shown in Appendix A. These were all made from cold-rolled steel and were not heat-treated since it was felt that by using the relatively soft lead no particular abuse would be experienced by the apparatus. This confidence was borne out by the experiment.

Since four dies were required, it was necessary to either make the dies removable from the cylinder or make four dies integral with the cylinder. Realizing that it would be impossible to extrude 100 percent of the billet and that the remainder would have to be removed from the cylinder, it was decided that the better arrangement would be to have the die detachable from the cylinder, thus facilitating the removal of the spent billet.

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Use was made of an anti-flashing ring between the ram and the billet. Great care was used in machining the cylinder hole and the ram so as to obtain a tight but movable fit. However, enough clearance was left to permit flashing of the lead between the cylinder and the ram. If allowed, this flashing eventually results in binding the ram. In order to alleviate this situation a small steel split ring was used as a seal between the lead and the ram face. See Figure 13. As the ram forced the ring into the lead, the tapered inner face of the ring caused the ring to expand outward, sealing off any lead which might try to slip between the ram and cylinder. This method worked very successfully.

The next consideration was that of lubrication. From experience it was known that some form of lubrication was required in the extrusion of lead and most references indicated some form of graphite. However, in this experiment the problem of lubrication was made complicated by the fact that there should be no lubrication on the interface. This, at the onset, ruled out the use of a liquid lubricant unless the interface could somehow be closed off. At first the notion of pressing the two billets together under extreme pressure in a closed container was tried, but with the pressures available this was unsuccessful. Since the lubricant recommended was some form of graphite and dry film graphite was available, the problem was solved. The billets, prior to extrusion, were sprayed with "DGF-123", a quick-drying product produced by the A. P. Products Corporation of Toledo, Ohio. This method proved to be successful in that it provided lubrication to the cylinder wall and still did not lubricate the interface. A small amount of liquid graphite was placed on the die face to facilitate the initial phase of the extrusion.

Figure 12 shows the apparatus as set up for extruding the lead billets.

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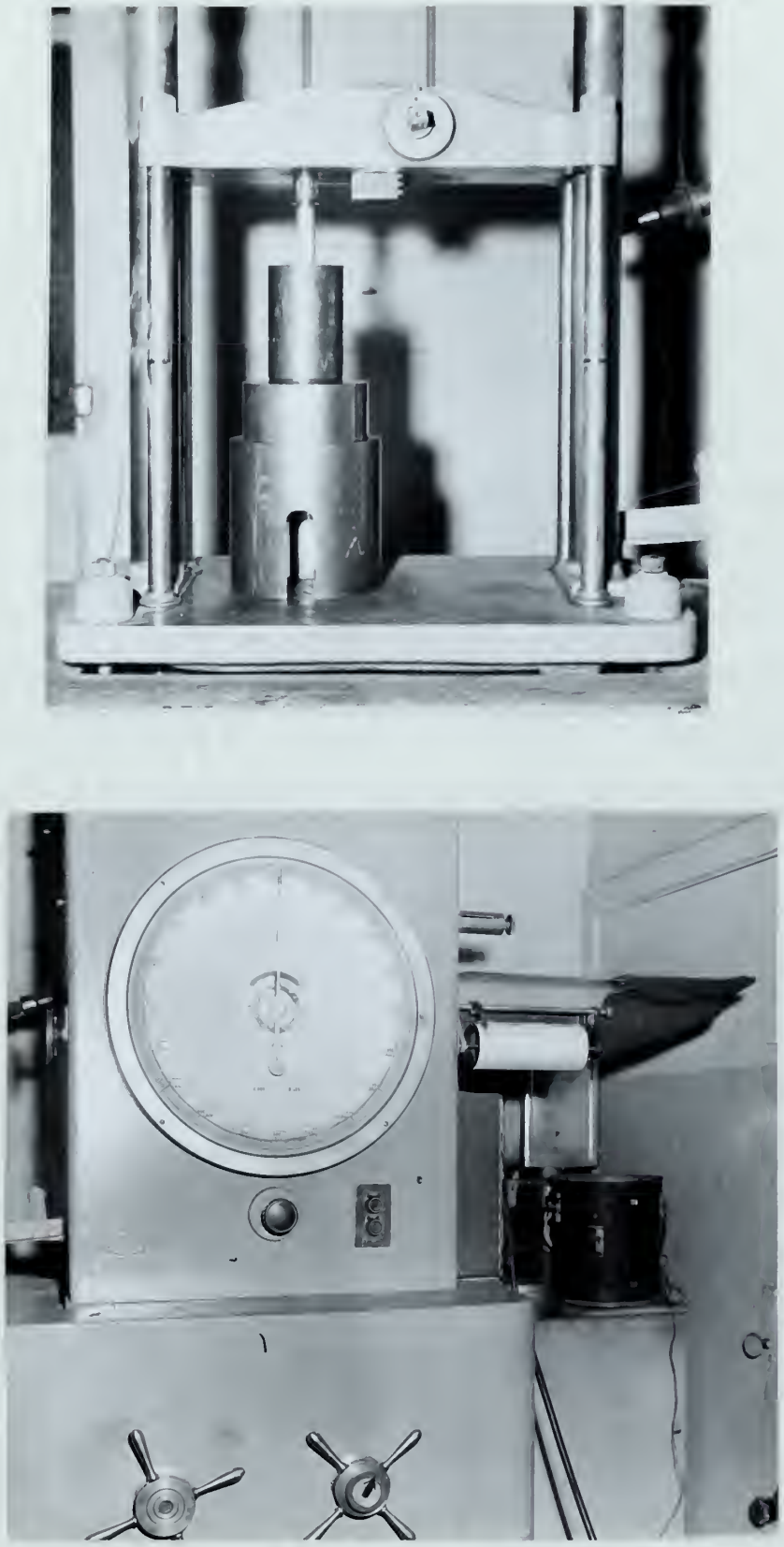

Figure 12 - Tinius-Olsen Tensile Testing Machine Used For Extrusion Testing

Figure 12 - Tinius-Olsen Tensile Testing Machine Used For Extension Testing

IV. PREPARATION OF THE BILLET

The three types of lead were obtained in pig form and were melted down in the laboratory under conditions which were intended to prevent any contamination which might have caused a variation in its properties. The molten lead was poured into a hollow graphite cylinder which had an inside diameter of 2 inches. This billet was cooled slowly in air and caused to solidify from the bottom up by using a torch to apply heat at the top. This was done in order to assure that no pipe would form.

After cooling, the billet was removed from the graphite cylinder and the top inch was sawed off and discarded. This billet was then extruded in a 100-ton extrusion press using a .756-inch die. The extrusion was performed at room temperature. These rods were then drawn down to .748-inch diameter on a regular drawing machine.

After cutting into 1½-inch length cylinders, the cylinders were faced off on one end and the required cone machined on the other. Each billet was labeled as to its cone angle and percent antimony. Although the accuracy of the angle as machined could not be attested to, it was the procedure that once the lathe was set up for cutting a particular angle, all the samples were done at once, both the male and female, to insure that all the angles were the same within that group of cone angle designation.

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V. ANALYSIS

A. Preparation of the Sample

The extrusions were performed in the order shown in Table I. Each extrusion was given a number and all pictures, diagrams, and calculations can be identified by this number and reference to Table I.

As each extrusion was completed, the extruded metal was scrutinized in order to locate some tell-tale sign by which the position of the interface could be determined. Usually this presented no particular problem because a definite discontinuity would develop. Sometimes where the two metals were of the same composition, finding the exact location of the interface was quite a problem and long test samples had to be taken. The direction of extrusion was scribed on the metal.

Since the information could only be obtained along the cross-section of the test sample, it was necessary first to embed the lead into a metallographic mounting substance called Casto-Mold, manufactured by the Cosmos Products, Inc., of New York City. This facilitated mounting the samples in a strong resiliant plastic without the application of heat.

Each sample was then ground down to the diameter by use of a wet-belt sander and the application of a great deal of water as a coolant for the lead. Extreme care was exercised in this process for the lead had a tendency to smear if too much pressure was applied, or if the lead was allowed to heat up. At first an attempt was made to mill each sample down, but this proved to be a great time-consuming process. By using the wet-belt sander, a sample was prepared in just a couple of minutes.

After this initial rough-grind, the sample was then further polished using emery paper down to 2/0 with liberal amounts of kerosene as a

E. Specimens

4. Preparation of the Sample

The extractions were performed in the order shown in Table E. Each extraction was given a number and all pertinent data, and calculations can be identified by this number and reference to Table 1.

As each extraction was completed, the extracted part was sectioned in order to locate more tail-tale sign by which the position of the interface could be determined. Usually this presented no particular problem because a definite discontinuity would develop. Positions where the two metals were of the same composition, limiting the exact location of the interface was quite a problem and long thin samples had to be taken. The direction of extrusion was scribed on the metal.

Since the information could only be obtained along the cross-section of the test sample, it was necessary first to mount the laminate a metallographic mounting substance called Bake-Lite, manufactured by the Cosmo Products, Inc., of New York City. This facilitated mounting the samples in a strong resilient plastic without the application of heat. Each sample was then ground down to the diameter by use of a wet-belt sander and the application of a great deal of water as a coolant for the land. Extreme care was exercised in this process for the land had a tendency to smear if too much pressure was applied, or if the land was allowed to heat up. At first an attempt was made to mill each sample down, but this proved to be a great time-consuming process. By using the wet-belt sander, a sample was prepared in just a couple of minutes.

After this initial rough-grind, the sample was then further polished using emery paper down to 5/0 with liberal amounts of kerosene as a

lubricant and coolant to prevent smearing. No finer paper than 2/0 was used because the interest was in the interface rather than in the grain structure of the lead.

At this point, many of the samples displayed the interface very clearly and needed no further preparation prior to photographing; however, some form of etching was called for to facilitate the photographic process. Three basic types of etches were used, depending upon the composition of the sample, namely:

(1) Glacial Acetic Acid

(2) Nitric Acid (concentrated)

(3) Hydrogen Peroxide (30 percent)

It will be recalled that each sample could be composed of any two of the three types of lead. If the two metals in the sample consisted of dissimilar metals, such as pure lead and 10 percent antimony lead, then a light cotton swabbing with full strength Glacial acetic acid was sufficient to clearly bring out the interface because the greater the percentage of antimony in the lead, the lighter in color would be the etch. Pure lead turned almost black.

When the two leads in the sample were of the same metal, such as pure lead and pure lead, then the problem was to try to burn out the interface with the hope that the grain structure at the interface would be weaker and thus more susceptible to a strong oxidizing agent. The first etching solution tried was:

16 parts H_2O

4 parts Acetic Acid (Glacial)

6 parts HNO_3

lubricant and coolant to prevent seizing. To clear paper down 2/0 was used because the interest was in the interface rather than in the grain structure of the lead.

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(2) Nitric Acid (concentrated)

(3) Hydrogen Peroxide (30 percent)

It will be recalled that each sample could be composed of any two of the three types of lead. If the two metals in the sample constituted of dissimilar metals, such as pure lead and 10 percent antimony lead, then a light cotton swabbing with full strength Glacial acetic acid was sufficient to clearly bring out the interface because the greater the percentage of antimony in the lead, the lighter in color would be the etch. Pure lead turned almost black.

When the two leads in the sample were of the same metal, such as pure lead and pure lead, then the problem was to try to burn out the interface with the hope that the grain structure at the interface would be weaker and thus more susceptible to a strong oxidizing agent. The first etching solution tried was:

16 parts H_2O

4 parts Acetic Acid (Glacial)

6 parts CrO_3

In many cases this solution was sufficient to bring out the interface. In some isolated cases the aforementioned solution was not successful and the following was used:

1 part H_2O_2 (30 percent)

1 part Acetic Acid (Glacial)

Each sample was then photographed and printed. A complete set of the photographs are presented in Appendix A.

B. Determination of Extrusion Constant

One of the few basic relationships which apply to the process of extrusion is the concept of the Extrusion Constant (K). This states that the extrusion pressure is proportional to the natural logarithm of the ratio of the initial to the final cross-sectional areas.

$$P = K \ln (A_1/A_2) \qquad (1)$$

where P = extrusion pressure (psi)

A_1 = cross-sectional area of pre-extruded billet (area)

A_2 = cross-sectional area of extruded billet (area)

K = Extrusion constant (psi)

This relationship requires that many conditions remain fixed during any series of extrusions. Thus, there is no particular value of K for a particular metal since so many other variables can effect K. Some examples of parameters which have a profound effect on K are: the ram speed, the temperature, the type and amount of lubrication, the type of extrusion, and the geometry of the dies.

Realizing that these factors all contributed to the determination of K, it was mandatory that the experiment be so conducted as to have these factors remain constant for all the tests. This was not too

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and the geometry of the die.

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temperature, the type and amount of lubrication, the type of extrusion,

particular metal alloys so many other variables can affect K. Some examples

series of extrusions. Thus, there is no particular value of K for a

This relationship requires that many conditions remain fixed during any

K = extrusion constant (psi)

A_2 = cross-sectional area of extruded billet (area)

A_1 = cross-sectional area of pre-extruded billet (area)

P = extrusion pressure (psi)

where

$$P = K \ln (A_1/A_2) \qquad (1)$$

ratio of the initial to the final cross-sectional area.

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extrusion is the concept of the Extrusion Constant (K). This states that

One of the few basic relationships which apply to the process of

3. Determination of Extrusion Constant

the photographs are presented in Appendix A.

Each sample was then photographed and printed. A complete set of

3 part Fe_2O_3 (30 percent)

3 part acetic Acid (Diluted)

The following was used:

In some instances where the aforementioned solution was not successful and

In many cases this solution was sufficient to bring out the interface.

difficult to achieve because of the nature of the factors involved. The only items which could not be absolutely fixed were the temperature and the lubrication. All the tests were conducted at room temperature which varied, over the period of tests, about 10°F. It was assumed that this variation did not effect the results within the accuracy desired. In the matter of the lubrication, it was realized that the exact amount of dry film graphite could not be repeated for each test, but that so little variation existed that this too was felt to be within the experimental error anticipated.

Thus, with all other conditions remaining fixed, K depended only on P, A_1, and A_2. A_1 and A_2 were accurately measurable since the cylinder and dies were machined to within .001-inch. From the inception of the design the area ratios were selected as definite parameters such that A_1/A_2 varied in steps 4, 9, 16, and 25. These are called the area reduction ratios or extrusion ratios (E.R.)

$$E.R. = A_1/A_2 \qquad (2)$$

It then follows:

E.R.	ln E.R.
4	1.39
9	2.20
16	2.77
25	3.22

Then for a given E.R., K is directly proportional to the extrusion pressure, if (1) is valid. During the actual process of the extrusion, the load being applied to the ram was being recorded by means of a revolving drum and stylus connected by linkages to the recording dials of the Tinius-Olsen machine. This resulted in a graph of load versus travel

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Thus, with all other conditions remaining fixed, K depended only on P, A_1, and A_2. A_1 and A_2 were accurately measurable since the cylinder and dies were machined to within .001-inch. From the inception of the design the area ratios were selected as definite parameters such that A_1/A_2 varied in steps $\frac{1}{4}$, $\frac{1}{9}$, $\frac{1}{16}$, and $\frac{1}{25}$. These are called the area reduction ratios or extrusion ratios (E.R.)

$$E.R. = A_1/A_2 \tag{2}$$

It then follows:

E.R.	ln E.R.
$\frac{1}{4}$	1.39
$\frac{1}{9}$	2.20
$\frac{1}{16}$	2.77
$\frac{1}{25}$	3.22

Then for a given E.R., K is directly proportional to the extrusion

of the ram. Knowing the cross-sectional area of the ram, it was possible to convert directly from the load reading to a pressure reading.

Determining that particular value of the load to use presented a problem since at no time was a constant value attained. In Figure 14, which is a typical example of the type of curve obtained from the machine, several interesting things can be noticed. Since the ram speed was constant, the initial load was applied at a constant rate and is evidenced by the characteristic straight line at the beginning of the plot. This is analogous to the proportional region of a stress-strain curve for metal. As the load finally reached the point where the metal was stressed beyond the elastic limit, the extrusion began. At this point, a definite maximum occurred which was the stress required to start the extrusion. Once the extrusion began, the stress dropped to a lower value and reflected that stress which was required to maintain the extrusion. For the direct type of extrusion, this value did not remain constant because the friction experienced by the billet was decreasing as the billet length was becoming shorter. This downward trend is very evident in all the curves and appeared to be of constant slope for all tests.

As the interface between the two metals approached the die, there appeared to be a definite discontinuity in the recorded curve. Depending on the metals involved and the angle of the cone, this discontinuity varied slightly. After this discontinuity passed through the die, then, once again, the stress (or load) settled down to the relatively constant extrusion pressure characteristic of the second billet material.

One thing very noticeable on all the curves was the harmonic-like vibration which occurred whenever a discontinuity passed through the die.

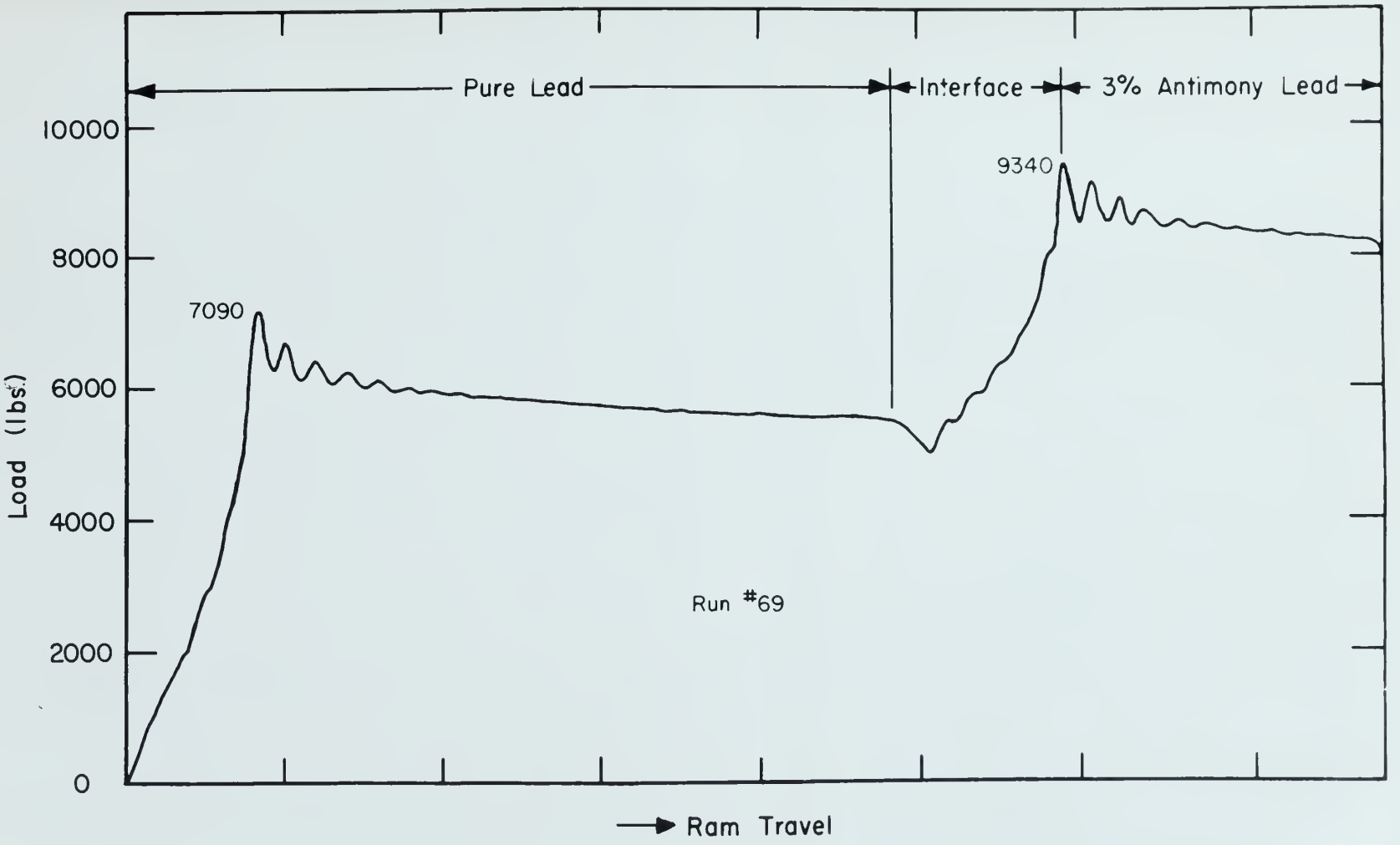

Figure 14 Typical Recording of Load vs Ram Travel from Tinius-Olsen Tensile Machine

This was always evident at the beginning of the extrusion and when the interface passed through the die. This phenomenon, not being of particular interest at this point, will be discussed in more detail later on.

In order to arrive at a mean value of the extrusion pressure for each region of the curve, a smooth curve was drawn through the slowly varying region, disregarding the initial peak value. Then by taking the value at the mid-point of this curve, the so-called mean extrusion pressure was determined. It is obvious that some engineering judgment had to be used in arriving at these values, but, as Table III indicates, very good values were obtained.

From this point it was a simple matter to arrive at K for each region and ultimately obtain K_1/K_2.

C. Determination of Extrusion Defect Area

The photographs shown in Appendix A clearly show the interface between the two extruded billets and the object now was to determine just what parameter would be used to classify the defect. Not knowing how the information would finally be used, it was decided to get as much information as possible from the photographs. Figure 15 is a typical example of an interface and shows the points and areas under consideration.

By using a calibrated planimeter, the area acbf was determined from the photograph. Since all the photographs were made to varying scales, these areas had to be multiplied by the area magnification of each photograph. This factor was arrived at by measuring the line de in both the photograph and the sample. By taking the squared ratio of these numbers, the area multiplication factor was determined. Then, by

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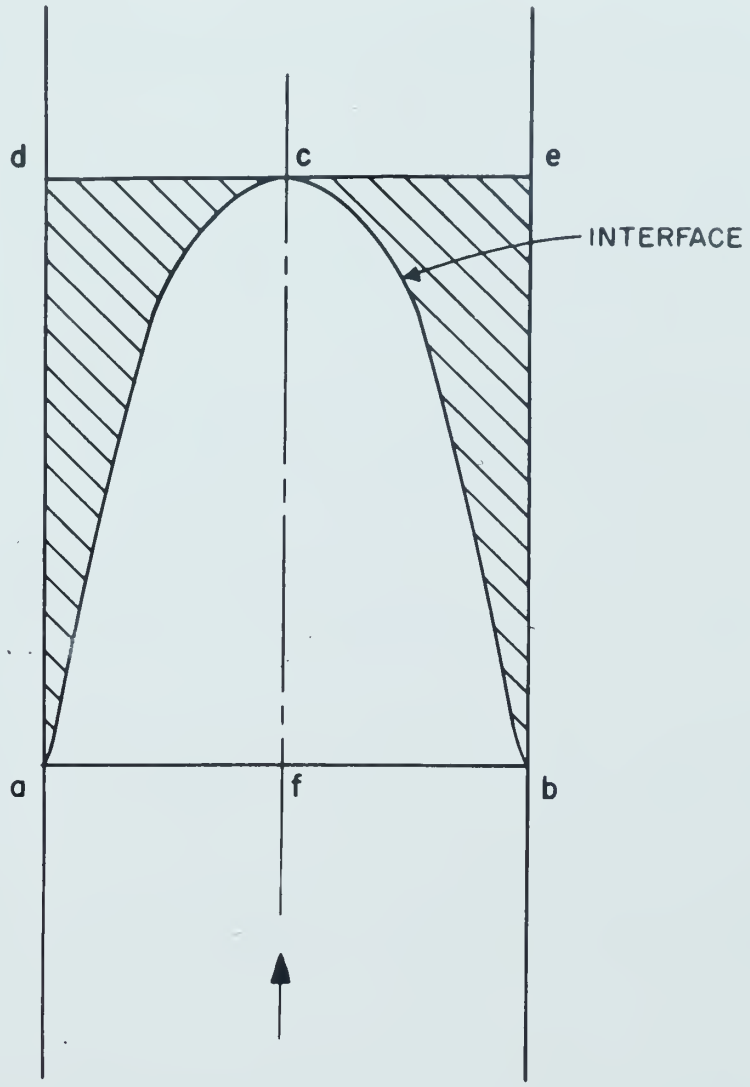

FIGURE 15

Parameters Used for Analyzing Extrusion Defects

dividing the area of Acbf of the photograph by this factor, the actual area of the sample for acbf was determined. See Table II.

It was also felt that the area acd plus ceb was of importance and so the line cf was measured, multiplied by line de, and divided by the area multiplication factor. This determined area adeb and from this area was subtracted the already known area acbf, giving area acd plus ceb.

Unfortunately, not all the interfaces were symmetrical about the centerline, and in these cases the line ab was drawn, connecting the points where the interface terminated at the outer edge. Point f was the mid-point of line ab. Line de was drawn through point c and perpendicular to the centerline of the extrusion. Results of these calculations are also shown in Table II.

dividing the area of $\underline{acbf}$ of the photograph by this factor, the actual area of the sample for $\underline{acbf}$ was determined. See Table II.

It was also felt that the area $\underline{gal}$ plus $\underline{ceb}$ was of importance and so the line $\underline{cf}$ was measured, multiplied by line $\underline{de}$, and divided by the area multiplication factor. This determined area $\underline{cdeb}$ and from this area was subtracted the already known area $\underline{acbf}$, giving area $\underline{ced}$ plus $\underline{ceb}$.

Unfortunately, not all the interfaces were symmetrical about the centerline, and in these cases the line $\underline{ab}$ was drawn, connecting the points where the interface terminated at the outer edge. Point $\underline{i}$ was the mid-point of line $\underline{ab}$. Line $\underline{de}$ was drawn through point $\underline{e}$ and perpendicular to the centerline of the extrusion. Results of these calculations are also shown in Table II.

TABLE II

EXTRUSION EXPERIMENTAL DATA

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (sq. In.)	Key
1	8040	8500	5800	6130	.947	.0393	.0925	.0572	E
2	16530	15400	11920	11100	1.072	.0968	.1545	.0577	D
3	9180	15400	6630	11100	.598	.0222	.0316	.0094	A
4	14480	8380	10440	6050	1.728	.0534	.1197	.0663	I
5	13590	12100	9810	8730	1.122	.0750	.1340	.0590	F
6	12690	8500	9160	6130	1.494	.0397	.0743	.0346	H
7	8490	12920	6450	9330	.692	.0227	.0338	.0111	B
8	16650	12920	12020	9330	1.288	.1088	.1590	.0502	G
9	12800	14270	9240	10290	.898	.0557	.0923	.0423	C
10	12680	11540	5780	5260	1.100	.1535	.2490	.0955	E
11	21750	20150	9910	9170	1.080	.0957	.1625	.0668	F
12	24900	22100	11330	10050	1.127	.1437	.2650	.1213	D
13	21900	13000	9970	5290	1.685	.1805	.3430	.1625	H

TABLE II

ATAD LATERAL DATA

Maneuver Designation	Maneuver Start Time (sec)	Maneuver Stop Time (sec)	Maneuver Duration (sec)	$\bar{q}$ (psf)	$\bar{q}S$ (lb)	Maximum Lateral Acceleration (ft/sec²)	Maximum Rudder Deflection (deg)	Maximum Aileron Deflection (deg)	Maximum Roll Rate (deg/sec)	Maximum Yaw Rate (deg/sec)
1	8000	8900	900	450	45000	1.141	2.5	2.5	2.5	2.5
2	15100	15700	600	1100	110000	1.155	2.5	2.5	2.5	2.5
3	21100	21900	800	1100	110000	1.155	2.5	2.5	2.5	2.5
4	27000	27900	900	1100	110000	1.155	2.5	2.5	2.5	2.5
5	32900	33700	800	1100	110000	1.155	2.5	2.5	2.5	2.5
6	38900	39700	800	1100	110000	1.155	2.5	2.5	2.5	2.5
7	44900	45700	800	1100	110000	1.155	2.5	2.5	2.5	2.5
8	50900	51700	800	1100	110000	1.155	2.5	2.5	2.5	2.5
9	56900	57700	800	1100	110000	1.155	2.5	2.5	2.5	2.5
10	62900	63700	800	1100	110000	1.155	2.5	2.5	2.5	2.5
11	68900	69700	800	1100	110000	1.155	2.5	2.5	2.5	2.5
12	74900	75700	800	1100	110000	1.155	2.5	2.5	2.5	2.5
13	81000	81800	800	1100	110000	1.155	2.5	2.5	2.5	2.5
14	87000	87900	900	1100	110000	1.155	2.5	2.5	2.5	2.5
15	93000	93800	800	1100	110000	1.155	2.5	2.5	2.5	2.5
16	99000	99800	800	1100	110000	1.155	2.5	2.5	2.5	2.5
17	105000	105900	900	1100	110000	1.155	2.5	2.5	2.5	2.5
18	111000	111800	800	1100	110000	1.155	2.5	2.5	2.5	2.5

TABLE II (Continued)

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (Sq. In.)	Key
14	24700	12450	11240	5670	1.985	.1430	.2320	.0890	I
15	13600	18450	6190	8380	.738	.0745	.1075	.0330	B
16	23750	19000	10820	8650	1.253	.1605	.2520	.0915	G
17	13600	21900	6190	9970	.622	.0718	.0907	.0189	A
18	20650	22200	9400	10100	.930	.0853	.1468	.0615	C
19	15640	14950	5650	5400	1.046	.0201	.0668	.0467	E
20	28300	25500	10220	9210	1.110	.1365	.1800	.0435	F
21	31150	30300	11250	10950	1.032	.1450	.2550	.1100	D
22	28300	17900	10220	6460	1.585	.0975	.2195	.1220	H
23	33900	17650	12230	6370	1.922	.0540	.1158	.0618	I
24	17900	24550	6470	8860	.730	.1285	.1760	.0475	B
25	31700	26500	11440	9580	1.195	.1980	.3800	.1820	G
26	18350	28650	6620	10350	.638	.1345	.1700	.0355	A
27	28500	29100	10280	10500	.978	.1255	.2050	.0795	C

TABLE II (Continued)

Model Number	Engine Speed (rpm)	Brake Power (hp)	Brake Torque (lb-ft)	Brake Specific Fuel Consumption (lb/hp-hr)	Brake Mean Effective Pressure (psi)	Fuel Flow Rate (lb/hr)	Brake Thermal Efficiency (%)	Fig.
S1	5000	30.0	31.5	.419	87.5	12.57	20.2	6
S2	4500	30.0	35.0	.419	87.5	12.57	20.2	6
S3	4000	30.0	39.3	.419	87.5	12.57	20.2	6
S4	3500	30.0	45.0	.419	87.5	12.57	20.2	6
S5	3000	30.0	52.5	.419	87.5	12.57	20.2	6
S6	2500	30.0	63.0	.419	87.5	12.57	20.2	6
S7	2000	30.0	78.8	.419	87.5	12.57	20.2	6
S8	1500	30.0	105.0	.419	87.5	12.57	20.2	6
S9	1000	30.0	157.5	.419	87.5	12.57	20.2	6
S10	5000	25.0	26.3	.419	72.9	10.48	24.2	6
S11	4500	25.0	29.2	.419	72.9	10.48	24.2	6
S12	4000	25.0	32.8	.419	72.9	10.48	24.2	6
S13	3500	25.0	37.5	.419	72.9	10.48	24.2	6
S14	3000	25.0	43.8	.419	72.9	10.48	24.2	6
S15	2500	25.0	52.5	.419	72.9	10.48	24.2	6
S16	2000	25.0	65.6	.419	72.9	10.48	24.2	6
S17	1500	25.0	87.5	.419	72.9	10.48	24.2	6
S18	1000	25.0	131.3	.419	72.9	10.48	24.2	6
S19	5000	20.0	21.0	.419	58.3	8.38	30.2	6
S20	4500	20.0	23.3	.419	58.3	8.38	30.2	6
S21	4000	20.0	26.3	.419	58.3	8.38	30.2	6
S22	3500	20.0	30.0	.419	58.3	8.38	30.2	6
S23	3000	20.0	35.0	.419	58.3	8.38	30.2	6
S24	2500	20.0	42.0	.419	58.3	8.38	30.2	6
S25	2000	20.0	52.5	.419	58.3	8.38	30.2	6
S26	1500	20.0	70.0	.419	58.3	8.38	30.2	6
S27	1000	20.0	105.0	.419	58.3	8.38	30.2	6
S28	5000	15.0	15.8	.419	43.7	6.29	40.3	6
S29	4500	15.0	17.5	.419	43.7	6.29	40.3	6
S30	4000	15.0	19.7	.419	43.7	6.29	40.3	6
S31	3500	15.0	22.5	.419	43.7	6.29	40.3	6
S32	3000	15.0	26.3	.419	43.7	6.29	40.3	6
S33	2500	15.0	31.5	.419	43.7	6.29	40.3	6
S34	2000	15.0	39.3	.419	43.7	6.29	40.3	6
S35	1500	15.0	52.5	.419	43.7	6.29	40.3	6
S36	1000	15.0	78.8	.419	43.7	6.29	40.3	6

TABLE II (Continued)

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (Sq. In.)	Key
28	19900	18350	6180	5700	1.085	.1005	.1650	.0645	E
29	33100	31000	10270	9630	1.068	.3950	.4640	.1610	F
30	36700	34900	11400	10850	1.052	.1235	.2250	.1015	D
31	31900	18350	9930	5700	1.742	—	—	.0760	H
32	40700	19000	12630	5910	2.135	.2600	.4350	.1750	I
33	21500	29000	6680	9020	.742	.3530	.4630	.1100	B
34	37100	30700	11520	9530	1.210	.3150	.4950	.1800	G
35	24550	37400	7630	11620	.657	.1325	.2100	.0775	A
36	36500	37100	11350	11520	.985	—	—		C
37	11440	9510	8270	6870	1.205	.0757	.1165	.0408	E
38	14720	13700	10620	9890	1.075	.0560	.0918	.0350	F
39	15150	16540	10940	11950	.916	.0479	.0700	.0221	D
40	15850	10180	11450	7350	1.558	.0378	.0682	.0304	H
41	18100	9510	13060	6870	1.904	.0564	.1132	.0568	I

Table II (continued)

Year	Beginning of Year Population (Thousands)	Births (Thousands)	Deaths (Thousands)	Natural Increase (Thousands)	Net Migration (Thousands)	Population Increase (Thousands)	End of Year Population (Thousands)	Crude Birth Rate (per 1,000)	Crude Death Rate (per 1,000)	Rate of Natural Increase (per 1,000)	Rate of Net Migration (per 1,000)	Rate of Population Increase (per 1,000)
1	1,000	40	20	20	0	20	1,020	40.0	20.0	20.0	0.0	20.0
2	1,020	41	20	21	0	21	1,041	40.2	19.6	20.6	0.0	20.6
3	1,041	42	21	21	0	21	1,062	40.3	20.2	20.2	0.0	20.2
4	1,062	43	21	22	0	22	1,084	40.5	19.8	20.7	0.0	20.7
5	1,084	44	22	22	0	22	1,106	40.6	20.3	20.3	0.0	20.3
6	1,106	45	22	23	0	23	1,129	40.7	19.9	20.8	0.0	20.8
7	1,129	46	23	23	0	23	1,152	40.7	20.4	20.4	0.0	20.4
8	1,152	47	23	24	0	24	1,176	40.8	20.0	20.8	0.0	20.8
9	1,176	48	24	24	0	24	1,200	40.8	20.4	20.4	0.0	20.4
10	1,200	49	24	25	0	25	1,225	40.8	20.0	20.8	0.0	20.8
11	1,225	50	25	25	0	25	1,250	40.8	20.4	20.4	0.0	20.4
12	1,250	51	25	26	0	26	1,276	40.8	20.0	20.8	0.0	20.8
13	1,276	52	26	26	0	26	1,302	40.8	20.4	20.4	0.0	20.4
14	1,302	53	26	27	0	27	1,329	40.7	20.0	20.7	0.0	20.7
15	1,329	54	27	27	0	27	1,356	40.6	20.3	20.3	0.0	20.3
16	1,356	55	27	28	0	28	1,384	40.5	19.9	20.6	0.0	20.6
17	1,384	56	28	28	0	28	1,412	40.4	20.2	20.2	0.0	20.2
18	1,412	57	28	29	0	29	1,441	40.3	19.8	20.5	0.0	20.5
19	1,441	58	29	29	0	29	1,470	40.2	20.1	20.1	0.0	20.1
20	1,470	59	29	30	0	30	1,500	40.1	19.7	20.4	0.0	20.4

TABLE II (Continued)

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (Sq. In.)	Key
42	8380	13700	6050	9890	.612	.0189	.0294	.0105	B
43	16540	14050	11950	10140	1.178	.0748	.1146	.0398	G
44	9970	15400	7200	11120	.648	.0248	.0341	.0093	A
45	14050	16050	10140	11600	.874	.0521	.0735	.0214	C
46	8610	9510	6220	6870	.905	.0655	.1056	.0550	E
47	14720	13820	10620	9980	1.063	.0522	.0833	.0311	F
48	17650	15400	12750	11120	1.146	.0799	.1162	.0363	D
49	15400	9730	11120	7020	1.585	.0478	.0838	.0360	H
50	17900	9280	12920	6700	1.930	.0770	.1498	.0728	I
51	10180	13820	7350	9980	.737	.0265	.0395	.0130	B
52	16540	13820	11950	9980	1.197	.0730	.1272	.0542	G
53	9850	15150	7100	10920	.650	.0289	.0417	.0128	A
54	13350	14150	9640	10220	.944	.0647	.0937	.0290	C
55	9730	8830	7020	6370	1.100	.0714	.1357	.0643	E

Table II (continued)

Element	Atomic Number	Electronic Configuration	Ionization Potential (eV)	r_a^3 (Å)	$\sqrt{r_a^3}$	Contribution to Total Polarizability ($r_a^3 \times$ Number of Electrons)	Contribution to Total Polarizability ($\sqrt{r_a^3} \times$ Number of Electrons)	Ref.
Z	40	$4d^2\,5s^2$	6.84	1.48	1.22	2.96	2.44	2
Nb	41	$4d^4\,5s$	6.88	1.52	1.23	3.04	2.46	2
Mo	42	$4d^5\,5s$	7.10	1.30	1.14	2.60	2.28	2
Ru	44	$4d^7\,5s$	7.37	1.07	1.03	2.14	2.06	2
Rh	45	$4d^8\,5s$	7.46	1.00	1.00	2.00	2.00	2
Pd	46	$4d^{10}$	8.33	0.48	0.69	0.96	1.38	2
Ag	47	$4d^{10}\,5s$	7.57	0.85	0.92	1.70	1.84	2
Cd	48	$4d^{10}\,5s^2$	8.99	0.46	0.68	0.92	1.36	2
In	49	$4d^{10}\,5s^2\,5p$	5.79	1.55	1.24	3.10	2.48	2
Sn	50	$4d^{10}\,5s^2\,5p^2$	7.34	1.08	1.04	2.16	2.08	2
Sb	51	$4d^{10}\,5s^2\,5p^3$	8.64	0.77	0.88	1.54	1.76	2
Te	52	$4d^{10}\,5s^2\,5p^4$	9.01	0.63	0.79	1.26	1.58	2
I	53	$4d^{10}\,5s^2\,5p^5$	10.45	0.49	0.70	0.98	1.40	2
Xe	54	$4d^{10}\,5s^2\,5p^6$	12.13	0.39	0.62	0.78	1.24	2
Cs	55	$5p^6\,6s$	3.89	3.34	1.83	3.34	1.83	2
Ba	56	$5p^6\,6s^2$	5.21	2.07	1.44	4.14	2.88	2
La	57	$5d\,6s^2$	5.61	1.80	1.34	3.60	2.68	2
Ce	58	$4f\,5d\,6s^2$	5.46	1.85	1.36	3.70	2.72	2
Pr	59	$4f^3\,6s^2$	5.42	1.87	1.37	3.74	2.74	2
Nd	60	$4f^4\,6s^2$	5.49	1.83	1.35	3.66	2.70	2
Pm	61	$4f^5\,6s^2$	5.55	1.80	1.34	3.60	2.68	2
Sm	62	$4f^6\,6s^2$	5.63	1.76	1.33	3.52	2.66	2
Eu	63	$4f^7\,6s^2$	5.67	1.74	1.32	3.48	2.64	2
Gd	64	$4f^7\,5d\,6s^2$	6.16	1.55	1.24	3.10	2.48	2
Tb	65	$4f^9\,6s^2$	5.85	1.66	1.29	3.32	2.58	2
Dy	66	$4f^{10}\,6s^2$	5.93	1.63	1.28	3.26	2.56	2
Ho	67	$4f^{11}\,6s^2$	6.02	1.60	1.26	3.20	2.52	2
Er	68	$4f^{12}\,6s^2$	6.10	1.57	1.25	3.14	2.50	2
Tm	69	$4f^{13}\,6s^2$	6.18	1.54	1.24	3.08	2.48	2
Yb	70	$4f^{14}\,6s^2$	6.25	1.52	1.23	3.04	2.46	2
Lu	71	$4f^{14}\,5d\,6s^2$	5.43	1.87	1.37	3.74	2.74	2
Hf	72	$4f^{14}\,5d^2\,6s^2$	6.65	1.39	1.18	2.78	2.36	2
Ta	73	$4f^{14}\,5d^3\,6s^2$	7.89	1.00	1.00	2.00	2.00	2
W	74	$4f^{14}\,5d^4\,6s^2$	7.98	0.97	0.98	1.94	1.96	2
Re	75	$4f^{14}\,5d^5\,6s^2$	7.87	1.01	1.00	2.02	2.00	2
Os	76	$4f^{14}\,5d^6\,6s^2$	8.7	0.74	0.86	1.48	1.72	2
Ir	77	$4f^{14}\,5d^7\,6s^2$	9.1	0.62	0.79	1.24	1.58	2
Pt	78	$4f^{14}\,5d^9\,6s$	8.96	0.66	0.81	1.32	1.62	2
Au	79	$4f^{14}\,5d^{10}\,6s$	9.22	0.58	0.76	1.16	1.52	2
Hg	80	$4f^{14}\,5d^{10}\,6s^2$	10.43	0.34	0.58	0.68	1.16	2
Tl	81	$4f^{14}\,5d^{10}\,6s^2\,6p$	6.11	1.57	1.25	3.14	2.50	2
Pb	82	$4f^{14}\,5d^{10}\,6s^2\,6p^2$	7.42	1.06	1.03	2.12	2.06	2
Bi	83	$4f^{14}\,5d^{10}\,6s^2\,6p^3$	7.29	1.10	1.05	2.20	2.10	2
Po	84	$4f^{14}\,5d^{10}\,6s^2\,6p^4$	8.43	0.78	0.88	1.56	1.76	2
At	85	$4f^{14}\,5d^{10}\,6s^2\,6p^5$	9.5	0.52	0.72	1.04	1.44	2
Rn	86	$4f^{14}\,5d^{10}\,6s^2\,6p^6$	10.74	0.37	0.61	0.74	1.22	2

TABLE II (Continued)

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (Sq. In.)	Key
56	13350	13590	9640	9820	.983	.0519	.0823	.0304	F
57	16420	16300	11850	11750	1.008	.0603	.0915	.0312	D
58	15050	9280	10860	6700	1.620	.0366	.0715	.0349	H
59	17900	9280	12920	6700	1.930	.0715	.1220	.0505	I
60	8040	14350	5820	10350	.562	.0115	.0170	.0055	B
61	17750	13900	12820	10040	1.275	.1175	.1785	.0610	G
62	10950	17200	7900	12420	.637	.0220	.0309	.0089	A
63	15500	15850	11180	11430	.979	.0379	.0565	.0186	C
64	15850	14500	7220	6600	1.092	.1285	.2130	.0845	E
65	21900	20600	9950	9370	1.063	.0624	.1329	.0705	F
66	25850	25100	11750	11400	1.032	.1015	.1748	.0733	D
67	23300	14050	10600	6390	1.658	.0858	.1236	.0378	H
68	26400	13480	12000	6130	1.958	.1305	.1426	.0121	I
69	13040	19000	5930	8640	.687	.0081	.0114	.0033	B

TABLE II (Continued)

Run Number	Total Pressure Behind Normal Shock (psia)	P_0 (psia)	M_∞	P_∞ (psia)	Cross-Sectional Area of Model Based on Base Area	Length of Model Based on Base Diameter	Drag Coefficient
45	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
46	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
47	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
48	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
49	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
50	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
51	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
52	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
53	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
54	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
55	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
56	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
57	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
58	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000
59	6577.0	6580	7.00	0.0267	0.0000	0.0000	0.0000

TABLE II (Continued)

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (Sq. In.)	Key
70	23900	19800	10850	9000	1.207	.1338	.1905	.0567	G
71	14040	23100	6380	10500	.608	.0103	.0138	.0035	A
72	20600	21850	9380	9930	.943	.0765	.1090	.0325	C
73	17100	15250	6180	5520	1.123	.0418	.0827	.0409	E
74	27400	25400	9900	9180	1.078	.0600	.0950	.0350	F
75	38500	36500	13900	13180	1.055	.0279	.0610	.0331	D
76	34200	17450	12350	6300	1.962	.1515	.2770	.1255	H
77	37200	17200	13420	6220	2.160	.1475	.2960	.1485	I
78	21500	28100	7770	10150	.766	.1345	.1520	.0175	B
79	29800	25200	10750	9080	1.182	.0702	.0967	.0265	G
80	21700	35100	7830	12650	.619	.0042	.0062	.0020	A
81	37400	36500	13500	13200	1.023	.0763	.0945	.0185	C
82	19800	17950	6150	5580	1.100	.0138	.0208	.0070	E
83	31300	29900	9730	9280	1.048	.0798	.1165	.0367	F
84	37900	35500	11750	11050	1.050	.1065	.1685	.0380	D

TABLE II (continued)

Number Evaluation Point	(ft) Point Area Pressure Evaluation	(psi)	p/p_s	(in. lb) Point Area Pressure Coefficient	(in. lb) Distance Point to Pressure Coefficient	(in. lb) Difference	Key
81	31500	32200	1.040	.1062	.1062	.0200	D
82	32400	33000	1.048	.0938	.1124	.0062	E
83	33300	33800	1.060	.0750	.1312	.0188	F
84	34200	34600	1.080	.0562	.1500	.0188	G
85	35100	35400	1.092	.0375	.1562	.0062	H
86	36000	36200	1.098	.0188	.1688	.0126	I
87	36900	37000	1.102	.0062	.1750	.0062	J
88	37800	37800	1.102	.0000	.1750	.0000	K
89	38700	38600	1.098	.0062	.1688	.0062	L
90	39600	39400	1.092	.0188	.1562	.0126	M
91	40500	40200	1.080	.0375	.1500	.0062	N
92	41400	41000	1.060	.0562	.1312	.0188	O
93	42300	41800	1.048	.0750	.1124	.0188	P
94	43200	42600	1.040	.0938	.1062	.0062	Q

TABLE II (Continued)

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (Sq. In.)	Key
85	29200	19350	9080	6020	1.510	.1075	.1845	.0770	H
86	38900	18550	12050	5770	2.090	.1368	.2660	.1292	I
87	21050	31500	6540	9780	.668	.0196	.0217	.0021	B
88	37000	29200	11480	9080	1.267	.2590	.3370	.0780	G
89	20900	34400	6500	10680	.609	.0025	.0055	.0030	A
90	31000	34700	9630	10780	.895	0	0	0	C
91	12900	11550	5870	5250	1.117	.0469	.0713	.0244	E
92	20800	20800	9460	9460	1.000	.0318	.0540	.0222	F
93	23450	23100	10670	10500	1.015	.0492	.0647	.0155	D
94	18800	12450	8550	5660	1.513	.0940	.1785	.0845	H
95	22400	12650	10180	5750	1.773	.0993	.1720	.0727	I
96	12250	18800	5580	8550	.654	.0612	.0727	.0115	B
97	22650	20100	10300	9140	1.128	.0483	.0800	.0317	G
98	12900	21050	5870	9580	.613	.0568	.0788	.0220	A
99	20000	21700	9100	9880	.921	.0583	.0932	.0349	C

TABLE II (Continued)

25	30000	31100	1200	1600	.767	.0003	.0137	.0010	.0149	.0010	25
26	35000	36200	1400	1900	.737	.0003	.0137	.0010	.0149	.0010	26
27	40000	41300	1600	2200	.727	.0003	.0137	.0010	.0149	.0010	27
28	45000	46400	1800	2500	.722	.0003	.0137	.0010	.0149	.0010	28
29	50000	51500	2000	2800	.717	.0003	.0137	.0010	.0149	.0010	29
30	55000	56600	2200	3100	.713	.0003	.0137	.0010	.0149	.0010	30
31	60000	61800	2400	3400	.710	.0003	.0137	.0010	.0149	.0010	31
32	65000	66900	2600	3700	.707	.0003	.0137	.0010	.0149	.0010	32
33	70000	72000	2800	4000	.704	.0003	.0137	.0010	.0149	.0010	33
34	75000	77100	3000	4300	.702	.0003	.0137	.0010	.0149	.0010	34
35	80000	82200	3200	4600	.700	.0003	.0137	.0010	.0149	.0010	35
36	85000	87300	3400	4900	.698	.0003	.0137	.0010	.0149	.0010	36
37	90000	92400	3600	5200	.696	.0003	.0137	.0010	.0149	.0010	37
38	95000	97500	3800	5500	.694	.0003	.0137	.0010	.0149	.0010	38
39	100000	102600	4000	5800	.693	.0003	.0137	.0010	.0149	.0010	39
40	105000	107700	4200	6100	.691	.0003	.0137	.0010	.0149	.0010	40
41	110000	112800	4400	6400	.690	.0003	.0137	.0010	.0149	.0010	41
42	115000	117900	4600	6700	.688	.0003	.0137	.0010	.0149	.0010	42
43	120000	123000	4800	7000	.687	.0003	.0137	.0010	.0149	.0010	43
44	125000	128100	5000	7300	.686	.0003	.0137	.0010	.0149	.0010	44
45	130000	133200	5200	7600	.685	.0003	.0137	.0010	.0149	.0010	45
46	135000	138300	5400	7900	.684	.0003	.0137	.0010	.0149	.0010	46
47	140000	143400	5600	8200	.683	.0003	.0137	.0010	.0149	.0010	47
48	145000	148500	5800	8500	.682	.0003	.0137	.0010	.0149	.0010	48
49	150000	153600	6000	8800	.681	.0003	.0137	.0010	.0149	.0010	49
50	155000	158700	6200	9100	.680	.0003	.0137	.0010	.0149	.0010	50

TABLE II (Continued)

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (Sq. In.)	Key
100	19900	16550	7190	5980	1.200	.1160	.1710	.0550	E
101	32650	25700	11800	9280	1.270	.0755	.1480	.0725	F
102	39000	33500	14080	12100	1.165	.1320	.2590	.1270	D
103	24300	15600	8780	5630	1.560	.1330	.2650	.1320	H
104	27900	17100	10060	6180	1.625	.1362	.2715	.1353	I
105	17200	24200	6220	8740	.712	.0456	.0662	.0206	B
106	38700	26900	13950	9720	1.435	.0715	.1245	.0530	G
107	16100	29200	5820	10550	.552	0	0	0	A
108	30300	31200	10940	11270	.972	.0785	.1450	.0665	C
109	19850	19250	6170	5980	1.030	.0162	.0200	.0038	E
110	38300	32800	11900	10180	1.168	.1240	.2440	.1200	F
111	37100	35100	11530	10900	1.058	.0818	.1430	.0388	D
112	38300	19950	11880	6200	1.915	.0277	.0414	.0137	H
113	35300	19450	10960	6040	1.815	0	0	0	I
114	20600	28800	6400	8950	.716	.1180	.1860	.0680	B

Table II (continued)

TABLE II (Continued)

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (Sq. In.)	Key
115	38500	30800	11950	9570	1.250	.4550	.6060	.1510	G
116	19350	34900	6020	10830	.555	.0041	.0064	.0023	A
117	36100	34700	11220	10780	1.042	.4240	.5950	.1710	C
118	12450	12450	5660	5660	1.000	.0418	.0619	.0201	E
119	19100	21050	8680	9580	.907	.0139	.0203	.0064	F
120	23200	23000	10550	10450	1.010	.0693	.1095	.0402	D
121	19500	12450	8880	5660	1.570	.0454	.0883	.0429	H
122	23200	11550	10550	5250	2.010	.0825	.1625	.0800	I
123	12450	19950	5660	9070	.625	.0076	.0098	.0022	B
124	24300	19050	11040	8660	1.275	.1225	.1872	.0647	G
125	11550	22500	5250	10220	.513	.0278	.0365	.0087	A
126	19450	24000	8850	10900	.812	.0379	.0537	.0158	C
127	15600	16200	5630	5850	.965	.0044	.0081	.0037	E
128	29000	26500	10450	9580	1.090	.0393	.0643	.0250	F
129	31300	30000	11300	10850	1.041	.1061	.1650	.0390	D

Table 11 (continued)

Test section	Pavement structure										
	Thickness of asphalt concrete surface (in.)	Thickness of asphalt concrete base (in.)	Thickness of granular base (in.)	E_1 (psi)	E_2 (psi)	E_3 (psi)	Cross-sectional area of load plate (sq. in.)	Load applied to load plate (lb)	Deflection measured at center of load plate (in.)	Deflection measured at 12 in. from center of load plate (in.)	Deflection measured at 24 in. from center of load plate (in.)
TS1	3.1	3.0	10.0	1,000	25,000	7,000	1,963	4,000	0.0130	0.0064	0.0026
TS2	3.1	3.0	10.0	1,000	25,000	7,000	1,963	8,000	0.0259	0.0128	0.0052
TS3	3.1	3.0	10.0	1,000	25,000	7,000	1,963	12,000	0.0389	0.0192	0.0078
TS4	3.1	3.0	10.0	1,000	25,000	7,000	1,963	16,000	0.0518	0.0256	0.0104
TS5	3.1	3.0	10.0	1,000	25,000	7,000	1,963	20,000	0.0648	0.0320	0.0130
TS6	3.1	3.0	10.0	1,000	25,000	7,000	1,963	24,000	0.0777	0.0384	0.0156
TS7	3.1	3.0	10.0	1,000	25,000	7,000	1,963	28,000	0.0907	0.0448	0.0182
TS8	3.1	3.0	10.0	1,000	25,000	7,000	1,963	32,000	0.1036	0.0512	0.0208
TS9	3.1	3.0	10.0	1,000	25,000	7,000	1,963	36,000	0.1166	0.0576	0.0234
TS10	3.1	3.0	10.0	1,000	25,000	7,000	1,963	40,000	0.1295	0.0640	0.0260
TS11	3.1	3.0	10.0	1,000	25,000	7,000	1,963	44,000	0.1425	0.0704	0.0286
TS12	3.1	3.0	10.0	1,000	25,000	7,000	1,963	48,000	0.1554	0.0768	0.0312
TS13	3.1	3.0	10.0	1,000	25,000	7,000	1,963	52,000	0.1684	0.0832	0.0338
TS14	3.1	3.0	10.0	1,000	25,000	7,000	1,963	56,000	0.1813	0.0896	0.0364
TS15	3.1	3.0	10.0	1,000	25,000	7,000	1,963	60,000	0.1943	0.0960	0.0390

TABLE II (Continued)

Extrusion Number	Extrusion Pressure First Metal (PSI)	Extrusion Pressure Second Metal (PSI)	K_1 (PSI)	K_2 (PSI)	K_1/K_2	Cross-Sectional Area of Defect (Sq. In.)	Length of Defect x Diameter (Sq. In.)	Difference (Sq. In.)	Key
130	24200	15150	8730	5570	1.570	.0199	.0427	.0228	H
131	31300	14800	11300	5350	2.110	.1372	.2570	.1198	I
132	15400	24600	5560	8880	.627	.0932	.1100	.0177	B
133	31500	24900	11350	9000	1.262	.1556	.2475	.0919	G
134	15600	32500	5640	11150	.508	.0059	.0072	.0013	A
135	26300	30700	9500	11100	.858	.0767	.1063	.0296	C
136	19250	18900	5980	5880	1.017	.0122	.0235	.0113	E
137	34500	29500	10720	9160	1.170	.0757	.1475	.0718	F
138	37500	35400	11650	11000	1.060	.0691	.0820	.0129	D
139	31000	19050	9650	5920	1.630	.1645	.2970	.1325	H
140	37500	17900	11650	5560	2.095	.2430	.4180	.1750	I
141	19450	29850	6030	9250	.652	0	0	0	B
142	37800	28500	11750	8850	1.325	.2075	.3770	.1695	G
143	18350	36500	5700	11350	.502	.0032	.0042	.0010	A
144	30800	34700	9580	10850	.883	.1425	.1850	.0425	C

TABLE II (continued)

VI. RESULTS AND DISCUSSION OF RESULTS

A. Normalized Extrusion Defects (Figures 16 - 28)

From the negatives obtained in photographing the etched interfaces, a normalized interface was drawn, using a photographic enlarger. On a piece of white paper a one inch line was drawn and the enlarger magnification was so adjusted as to make the diameter of the extrusion at the interface coincide with this drawn line. A pencil sketch was then made of the interface. Thus, all 144 samples were normalized, as it were, to a common one inch base. In redrawing the grouped sketches shown in the figures, a free hand was taken in making the interfaces symmetrical about the centerline, since very few of the samples were truly symmetrical.

In the grouping of the normalized defects, it was planned to group first of all, all those extrusions in which the metal compositions were identical. Thus in Figure 16-a is seen only those cases where pure lead was pushing pure lead for a particular extrusion ratio of 4. The only variation in Figure 16-a, and all the subsequent figures, is the preset cone angle. The numbers inside the parenthesis indicate this angle and those numbers outside indicate the extrusion number tabulated in Table I.

Figures 16 - 18 are all at an extrusion ratio of 4, whereas Figures 19 - 22 are at an extrusion ratio of 9. This pattern continues throughout the remainder of the figures.

In analyzing these curves one must bear in mind that as the defect curve approaches the outer edge in many cases it becomes parallel to this edge and the determination of the cut off point is almost impossible. For this reason, it is wise to utilize two parameters, or in effect, to observe two characteristics of the curves. The most important thing to

VI. ANALYSIS AND DISCUSSION OF RESULTS

A. Normalized Extrusion Defects (Figures 16 - 24)

From the negatives obtained in photographing the etched interfaces, a normalized interface was drawn, using a photographic enlarger. On a piece of white paper a one inch line was drawn and the enlarger magnification was so adjusted as to make the diameter of the extrusion at the interface coincide with this drawn line. A pencil sketch was then made of the interface. Thus, all 144 samples were normalized, as it were, to a common one inch base. In retracing the profiled sketches shown in the figures, a free hand was taken in making the interface symmetrical about the centerline, since very few of the samples were truly symmetrical.

In the grouping of the normalized defects, it was planned to group first of all, all those extrusions in which the metal components were identical. Thus in Figure 16-a is seen only those cases where pure lead was pushing pure lead for a particular extrusion ratio of R. The only variation in Figure 16-a, and all the subsequent figures, is the press cone angle. The numbers inside the parenthesis indicate this angle and those numbers outside indicate the extrusion number tabulated in Table I.

Figures 16 - 18 are all at an extrusion ratio of R, whereas Figures 19 - 22 are at an extrusion ratio of 9. This pattern continues throughout the remainder of the figures.

In analyzing these curves one must bear in mind that as the defect curve approaches the outer edge in any case it becomes parallel to this edge and the determination of the cut off point is almost impossible. For this reason, it is wise to neglect one parameter, or in effect, to observe two characteristics of the curves. The most important thing to

observe is the overall shape of the curve, especially the region near the vertex, and secondly the relative heights, or as is commonly referred to as the defect length. Recall that these curves are normalized and that comparison of height will have no justification between varying extrusion ratios. In the early stages of the experiment it was thought that the included angle at the vertex would lend itself as a convenient parameter but these figures show that little or no information would be gained from this point of view.

It might be well to mention at this point that the area included under these curves is not the so-called defect area as determined in Table II and used subsequently for analysis. Recall that the defect area is the shaded portion as shown in Figure 15.

Certain basis results are evident from these curves. This information, in itself, is not profound but merely agrees with generally well-known characteristics of the extrusions.

1. As the extrusion ratio increases, other variables being fixed, the defect length increases.

2. As the extrusion ratio increases, other variables being fixed, the interface vertex angle becomes more acute.

3. Generally, but not in all cases, as the preshaped cone angle is increased from the flat interface, the defect becomes less and the vertex becomes flatter.

Other characteristics seem to show certain trends which are either in disagreement with present theory or are not found in present day

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observe in the overall shape of the curve, especially the region near the

references. Briefly mentioned below are these trends which will be analyzed further using defect area parameter:

1. For a given extrusion ratio and cone angle, as the K_1/K_2 ratio is initially increased, there is a steady increase to the defect length, however as the K_1/K_2 ratio exceeds unity and extends out to about 1.5, there is a sharp drop in the defect length. After this drop, with the K_1/K_2 ratio increasing still further, the defect length increases still further.

2. For low extrusion ratios, variation in angle or metal composition shows little effect on the extrusion defect length or shape of the vertex. At high extrusion ratios, small variations in any variable produce tremendous changes in the shape of the defect.

3. Formation of voids, which will be covered separately.

4. The formation of reverses or "dimples" in the interface occurred with equal probability at cone angles of 10° and 15° and did not occur at 0° and 5°.

5. Increasing the cone angle did not necessarily reduce the defect.

6. No simple rule existed which would allow one to predict interface shapes.

reference. Briefly mentioned below are three trends which will be analyzed further using defect tree parameter.

1. For a given extrusion ratio and cone angle, as the K_I/K_S ratio is initially increased, there is a steady increase to the defect length, however as the K_I/K_S ratio exceeds unity and extends out to about 1.5, there is a sharp drop in the defect length. After this drop, with the K_I/K_S ratio increasing still further, the defect length increases still further.

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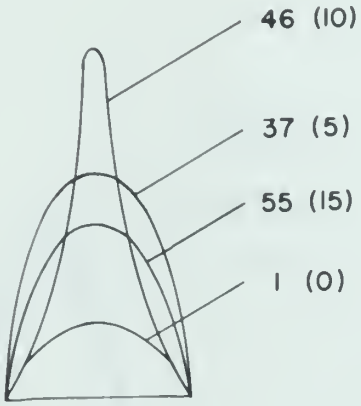
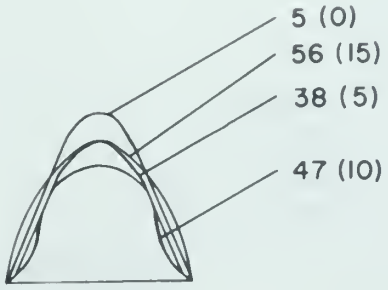


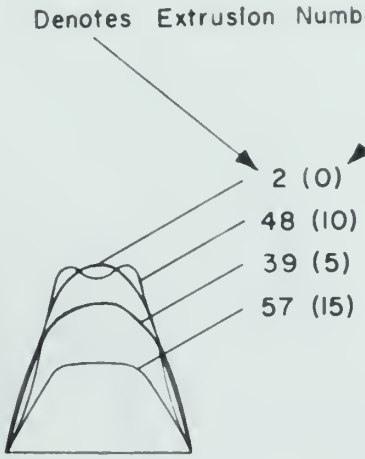
P→P
ER=4

Fig. 16-a



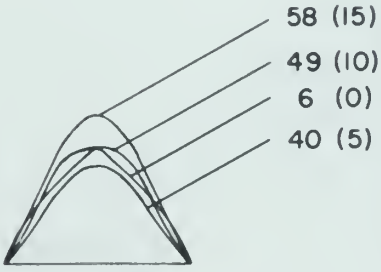
3→3
ER=4

Fig. 16-b



10→10
ER= 4

Fig. 16-c



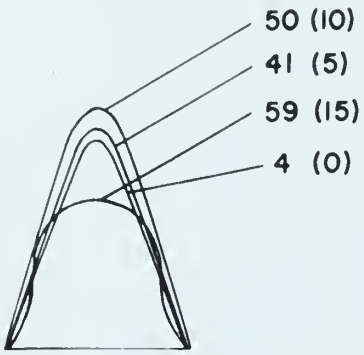
P→3
ER= 4

Fig 16-d

Indicates That Pure Lead is Pushing 3% Antimony Lead

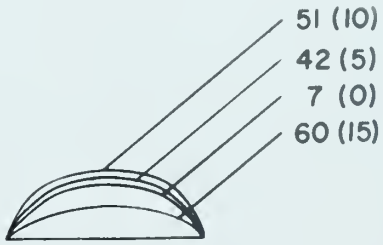
Extrusion Defects Normalized to Common Base

Figure 16



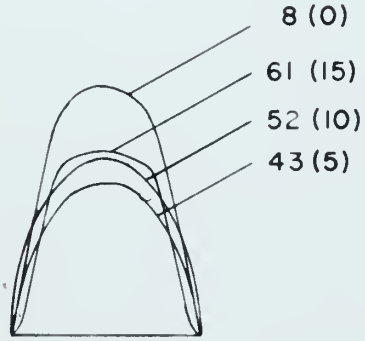
P → 10
ER = 4

Fig. 17-a



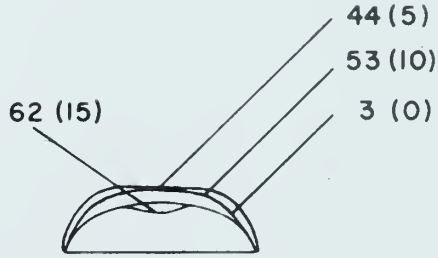
3 → P
ER = 4

Fig. 17-b



3 → 10
ER = 4

Fig. 17-c

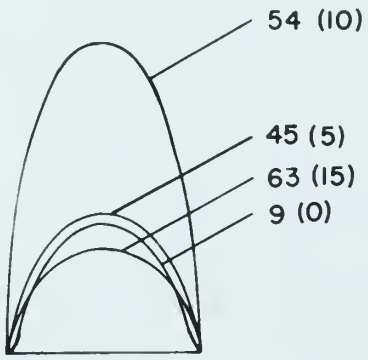


10 → P
ER = 4

Fig. 17-d

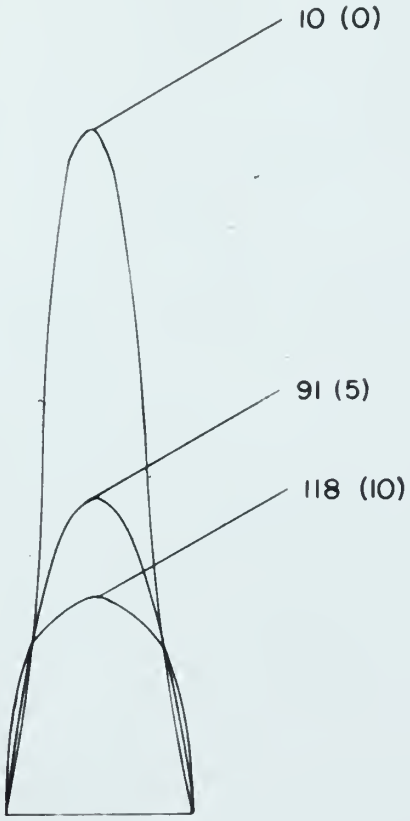
Extrusion Defects Normalized to Common Base

Figure 17



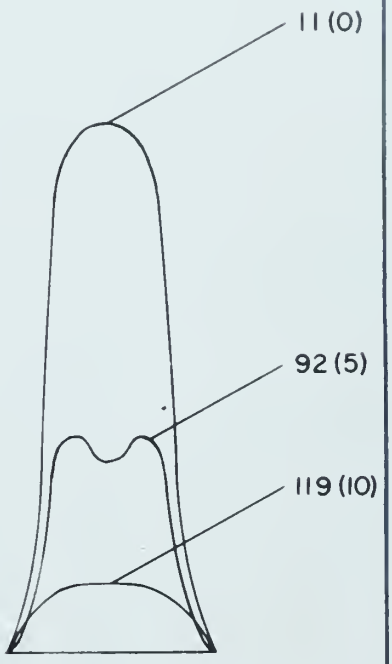
Extrusion Defects Normalized to Common Base

Figure 18



P→P
ER=9

Fig. 19–a

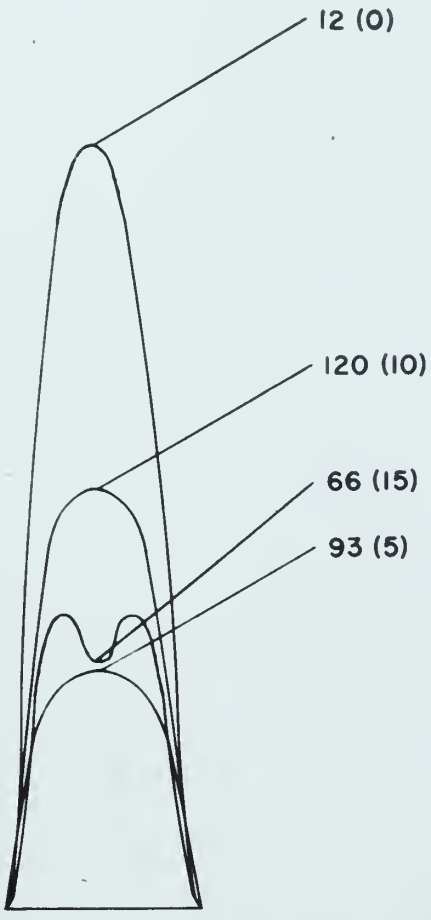


3→3
ER=9

Fig. 19–b

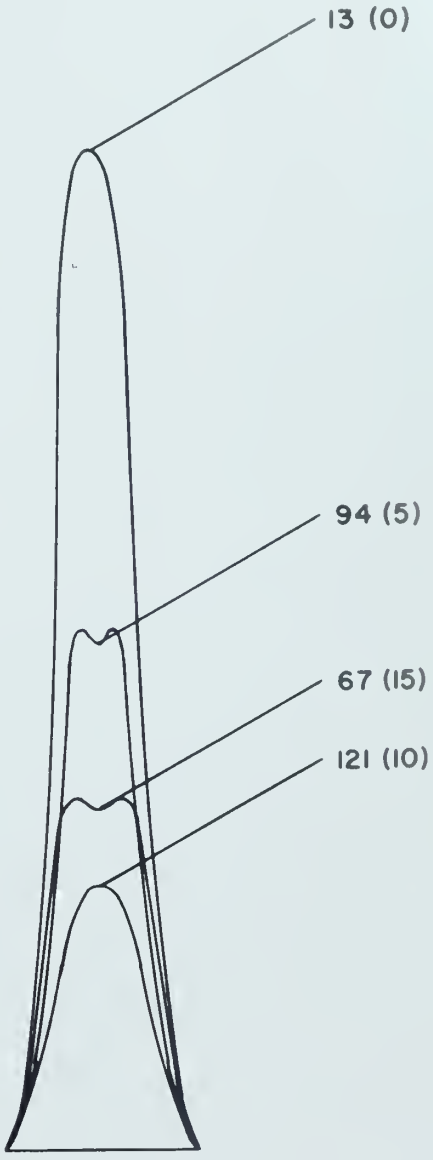
Extrusion Defects Normalized to Common Base

Figure 19



10→10
ER= 9

Fig. 20-a

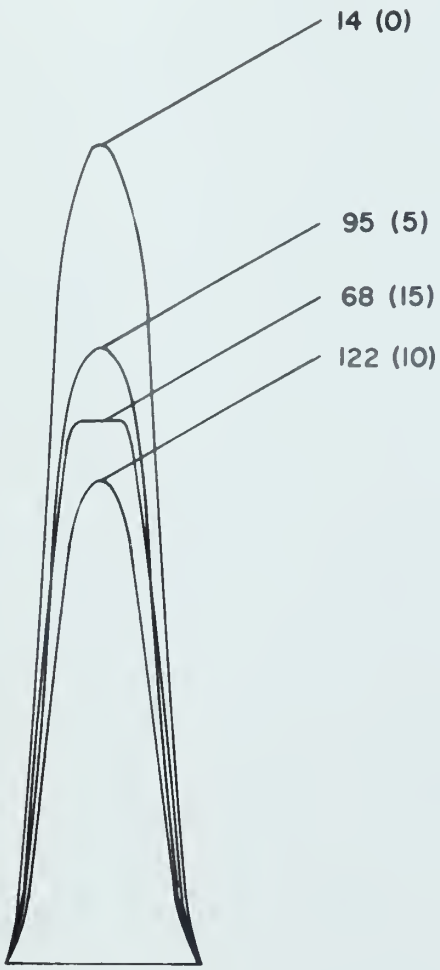


P→3
ER=9

Fig. 20-b

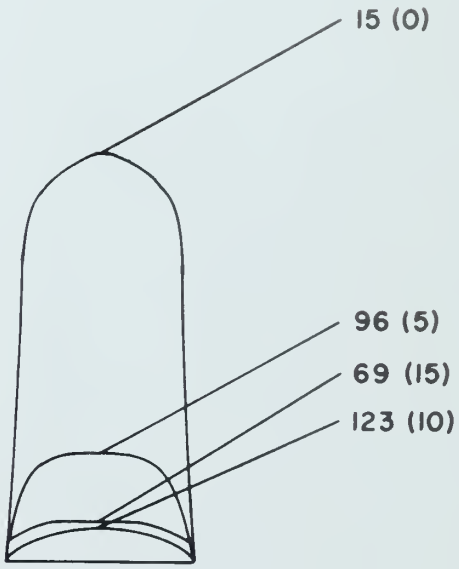
Extrusion Defects Normalized to Common Base

Figure 20



P→10
ER=9

Fig. 21-a

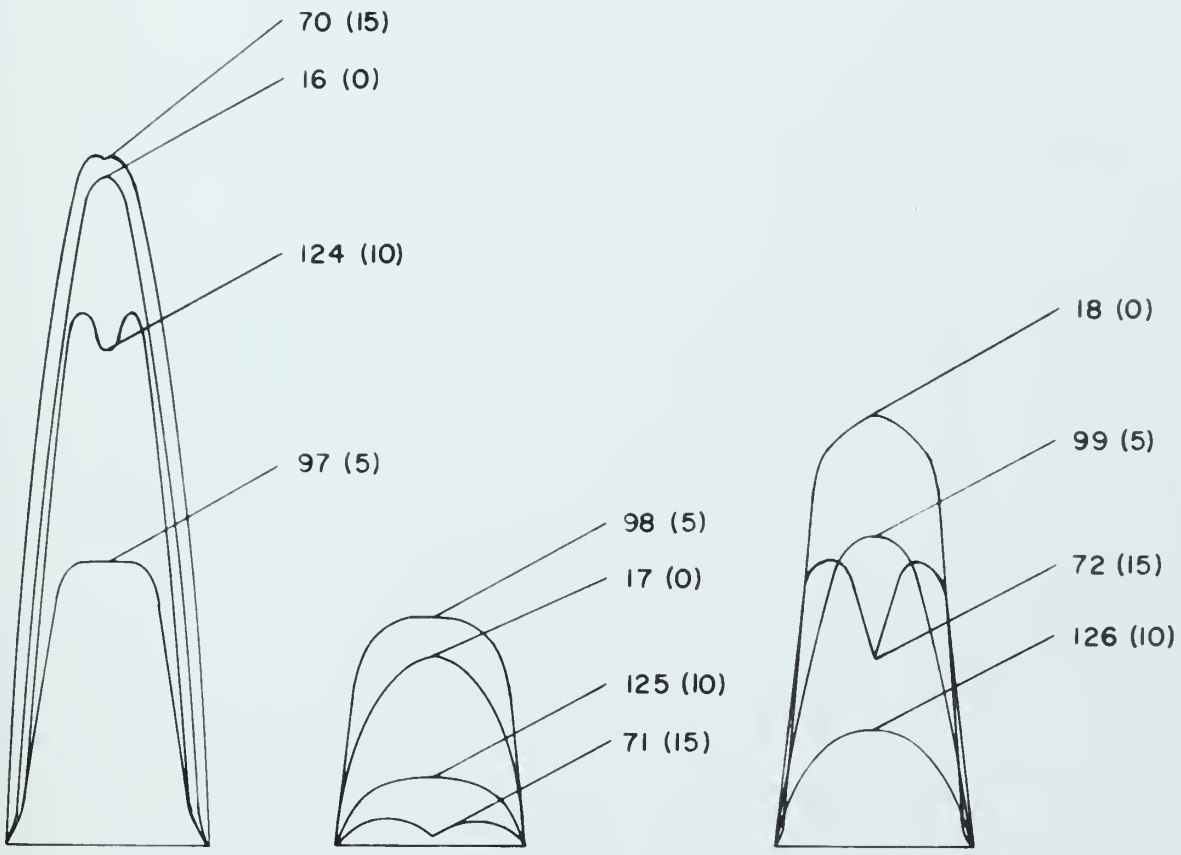


3→P
ER=9

Fig. 21-b

Extrusion Defects Normalized to Common Base

Figure 21



3→10
ER = 9

Fig. 22-a

10→P
ER = 9

Fig. 22-b

10→3
ER = 9

Fig. 22-c

Extrusion Defects Normalized to Common Base

Figure 22

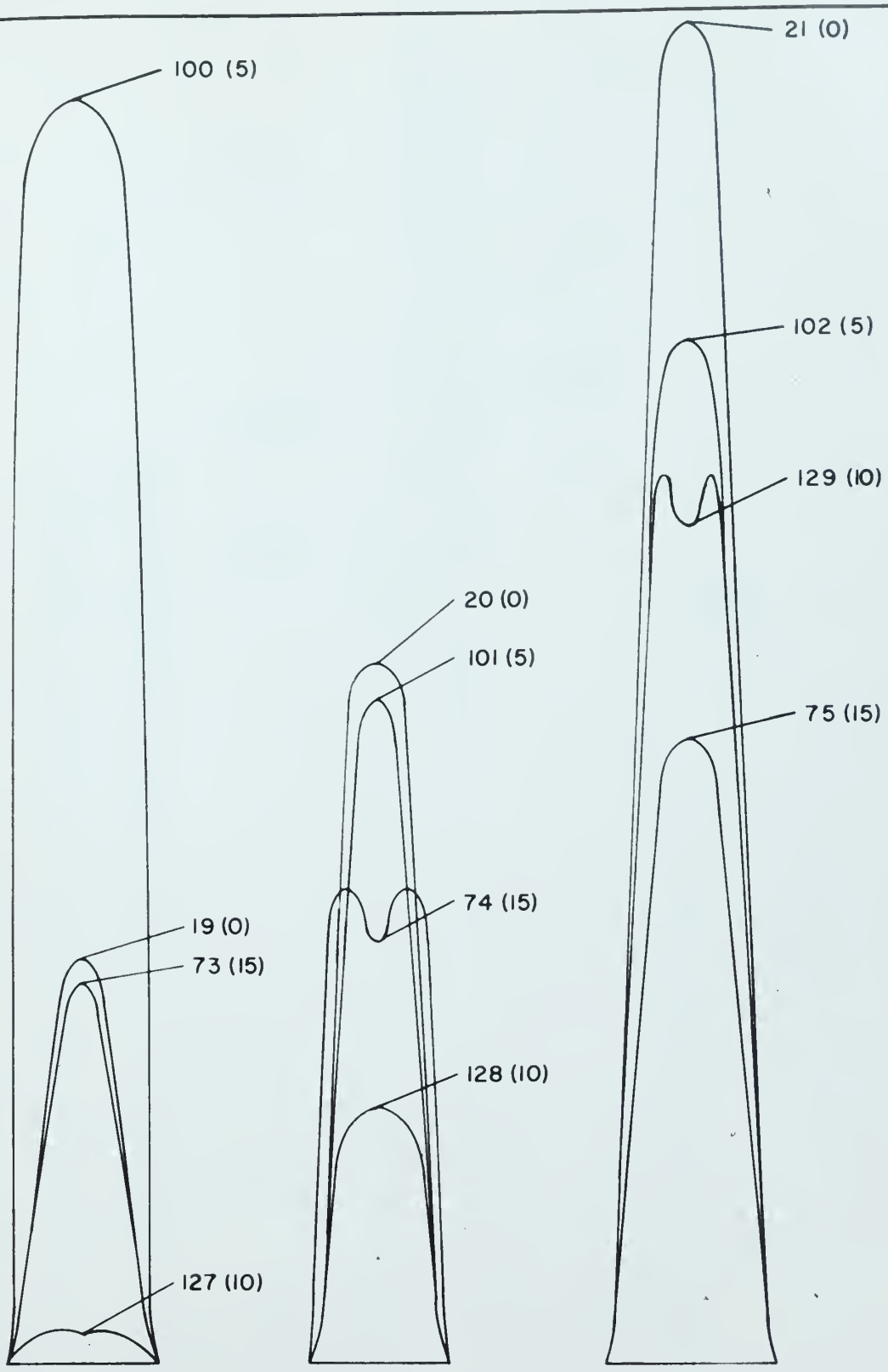


Figure 23 Extrusion Defects Normalized to Common Base

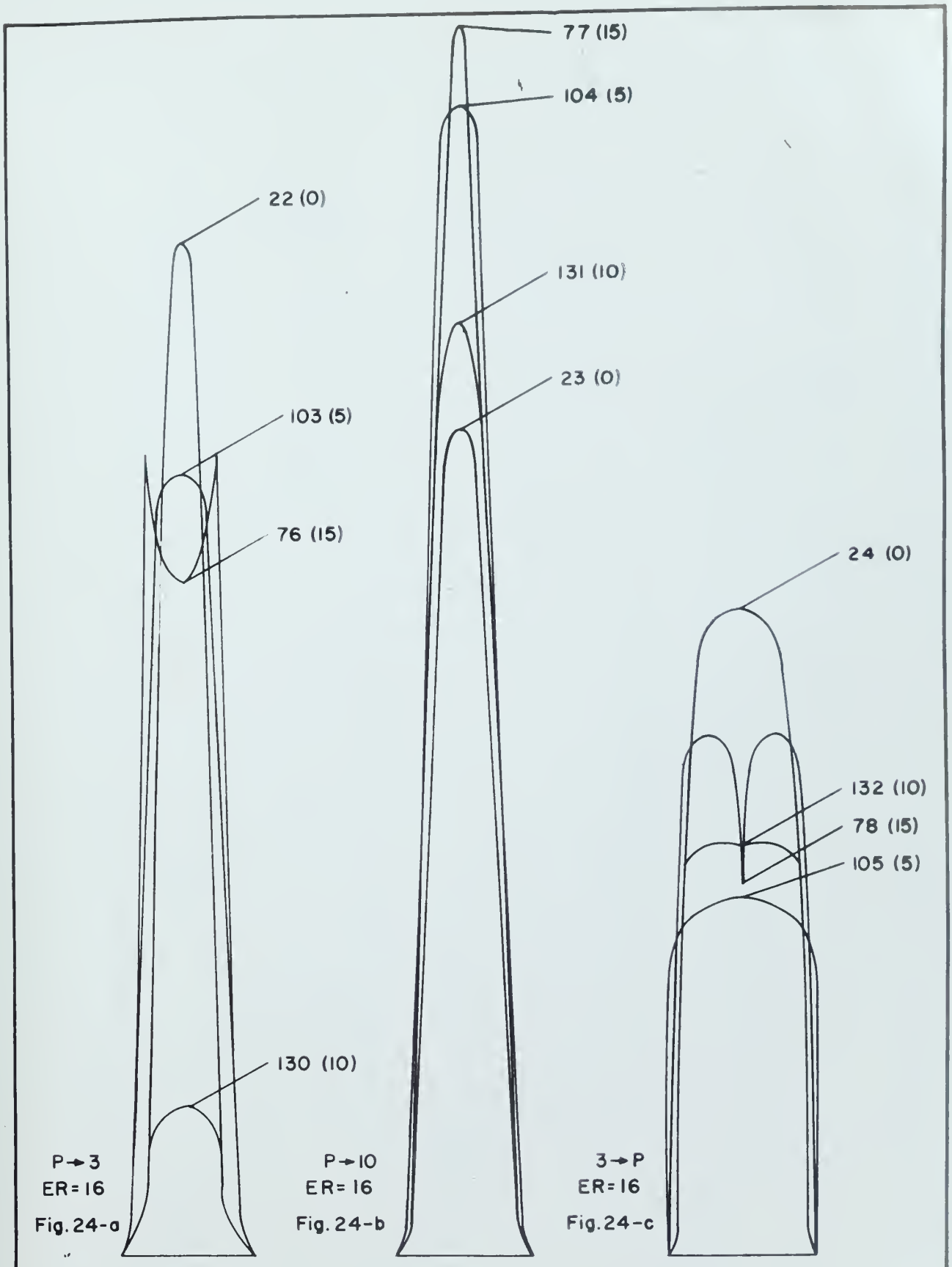
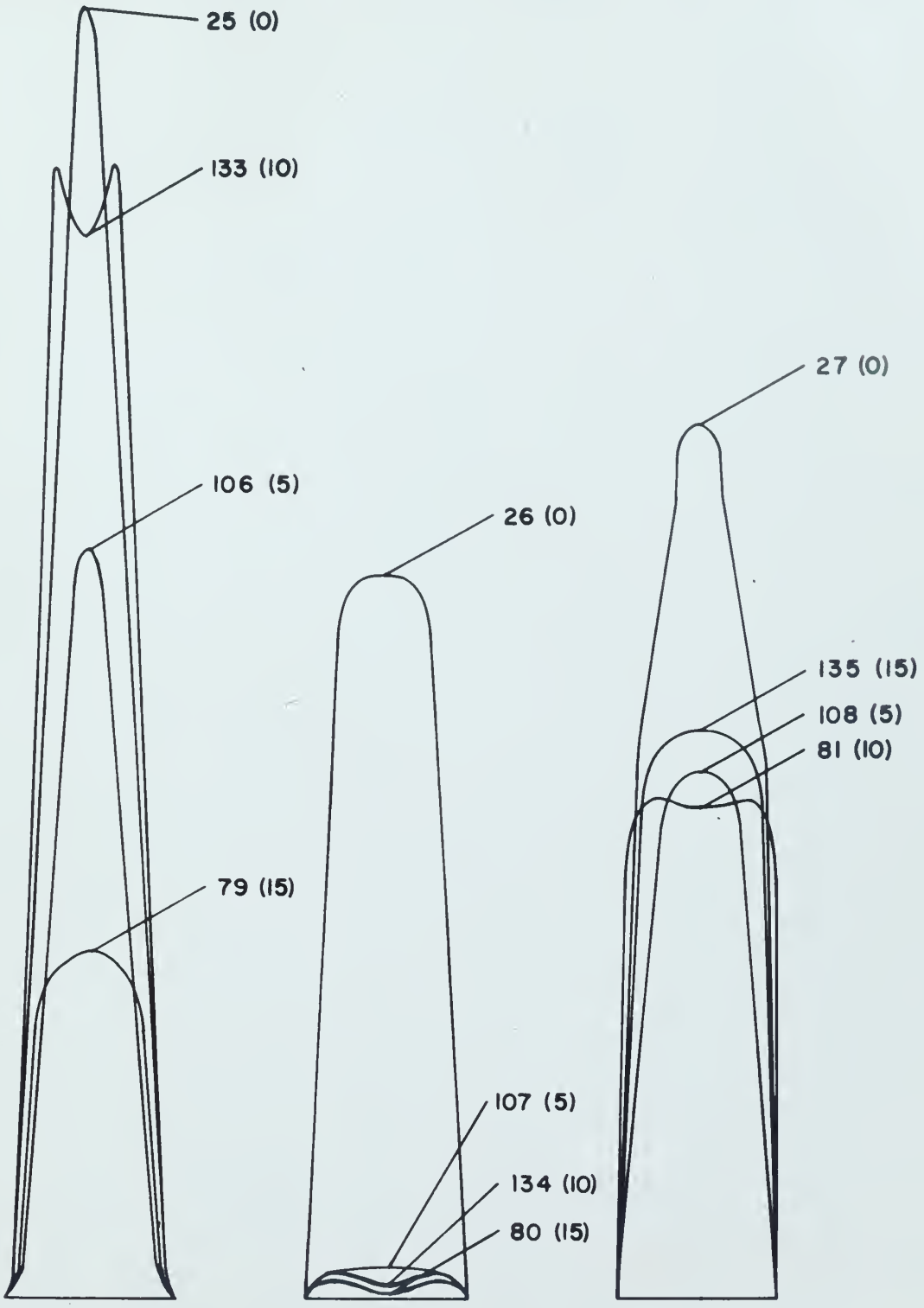


Figure 24 Extrusion Defects Normalized to Common Base



3→10
ER=16
Fig. 25–a

10→P
ER=16
Fig. 25–b

10→3
ER=16
Fig. 25–c

Figure 25 Extrusion Defects Normalized to Common Base

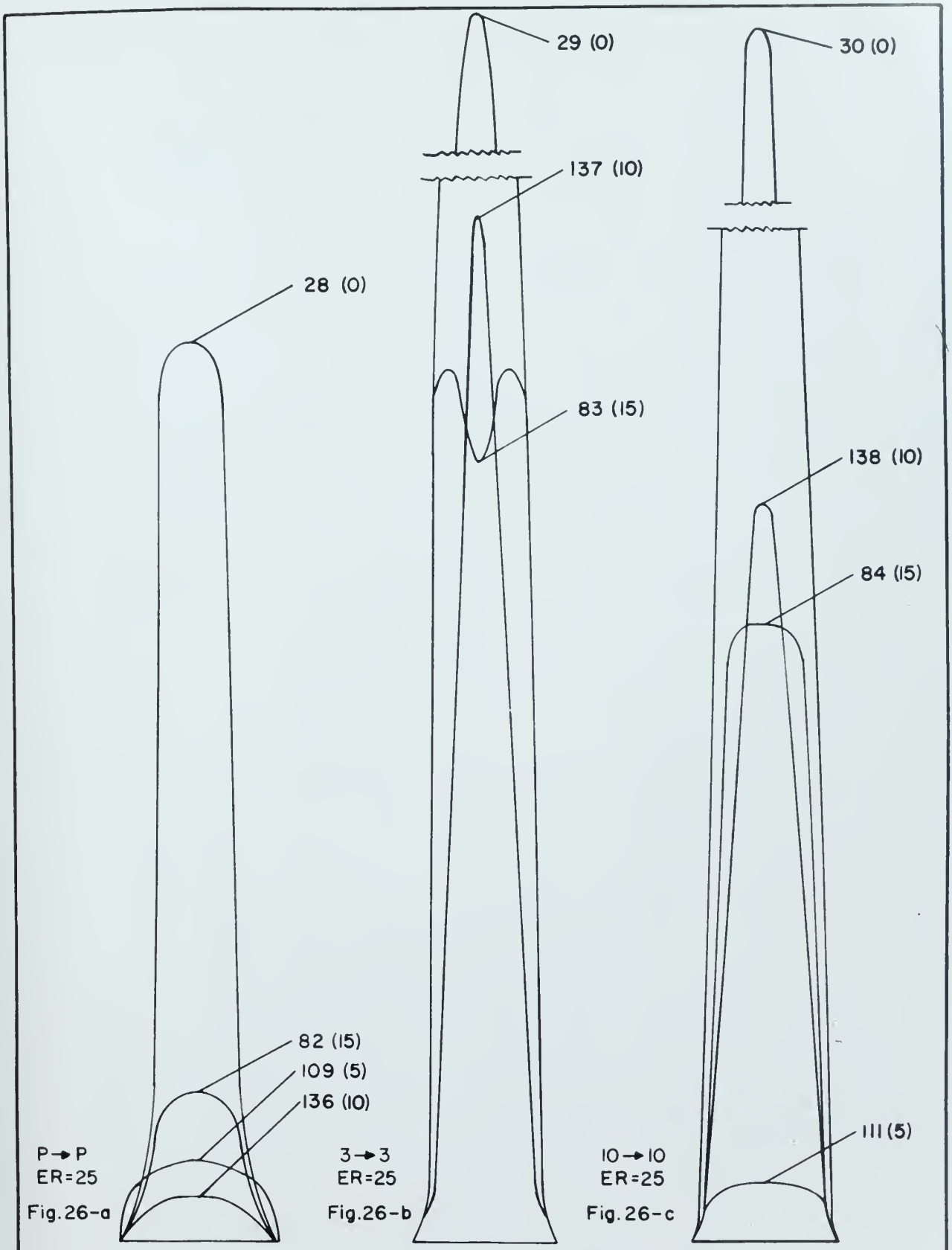
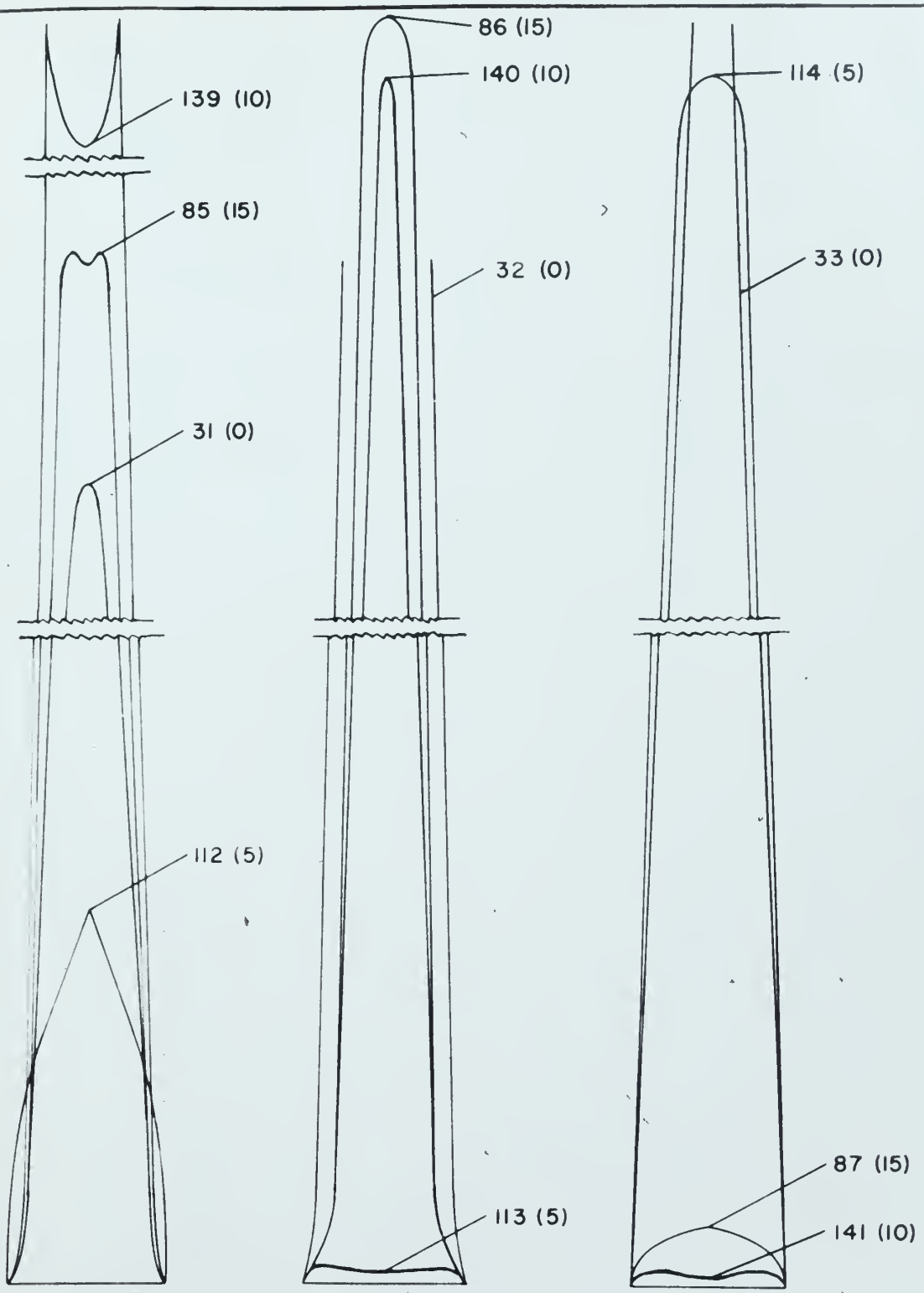


Figure 26 Extrusion Defects Normalized to Common Base

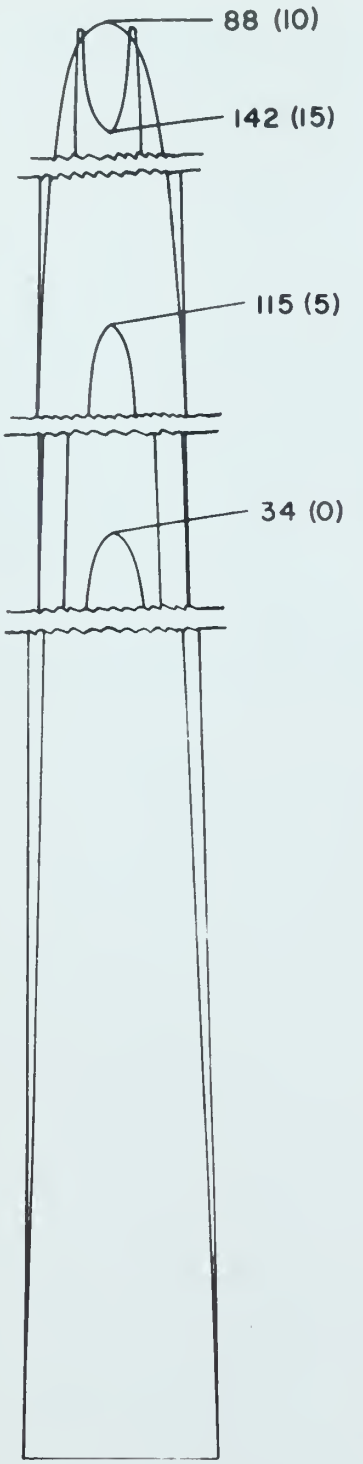


P→3
ER=25
Fig. 27–a

P→10
ER=25
Fig. 27–b

3→P
ER=25
Fig. 27–c

Figure 27 Extrusion Defects Normalized to Common Base



3 → 10
ER = 25

Fig. 28 – a

10 → P
ER = 25

Fig. 28 – b

10 → 3
ER = 25

Fig. 28 – c

Extrusion Defects Normalized to Common Base

Figure 28

B. Effect of Varying K_1/K_2 Ratio (Figures 29 - 36)

Figures 29 - 32 show the effect on the defect area with variation of the K_1/K_2 ratio. Information to plot these curves was obtained from Table II.

Since the metal used for each classification came from the same batch and can be assumed to be homogeneous, it might be suspected that the K_1/K_2 ratio for all the P- P extrusions, for example, would be the same. This was basically true, but since a particular K_1/K_2 value was found for each run, that value was plotted. It was of interest to determine the average value for all the various combinations and the results are shown in Table III.

TABLE III

TYPE	K_1/K_2	METAL COMBINATION
A	.596	10- P *
B	.683	3- P
C	.934	10- 3
D	1.053	10- 10
E	1.065	P- P
F	1.081	3- 3
G	1.245	3- 10
H	1.635	P- 3
I	1.948	P- 10

*Indicates 10 percent antimony lead pushing pure lead.

B. Effect of Varying K_1/K_2 Ratio (Figures 29 - 35)

Figures 29 - 32 show the effect on the defect area with variation of the K_1/K_2 ratio. Information to plot these curves was obtained from Table II.

Since the metal used for each classification came from the same batch and can be assumed to be homogeneous, it might be suspected that the K_1/K_2 ratio for all the P- P extrusions, for example, would be the same. This was basically true, but since a particular K_1/K_2 value was found for each run, that value was plotted. It was of interest to determine the average value for all the various combinations and the results are shown in Table III.

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H	1.635	P- 3
I	1.948	P- 10

*Indicates 10 percent antimony lead pushing pure lead.

The type designation was assigned so that Type A had the lowest K_1/K_2 ratio. Of interest is the fact that for Types D, E, and F, the K_1/K_2 ratio is slightly above 1.00. This is completely understandable if one recognizes that part of the load registered by the tensile machine is due to the friction between the lead and the cylinder wall. In the beginning the friction is greatest because there is more friction area. As the extrusion continues this area is reduced and consequently the friction is reduced, giving a lower reading for the second billet than the first.

Note also the very good agreement found in Types D, E, and F as to variation in K_1/K_2. This would give credence to the values obtained for the other types.

Table IV is a compilation of the extrusion constants (K) for the metals used, depending upon whether it was the first or second billet out of the die. These values agree fairly well with published data, but as was stated earlier, so many other variables enter into the determination of K that before comparisons can be made, the complete picture must be analyzed as to temperature, lubrication, die geometry, and ram speed. Sufficient, however, is the fact that K did remain a constant for this series of experiments.

Referring again to the series of curves plotted in Figures 29 - 32, it will be noted that they are all similar to a modified S-curve. At the low values of K_1/K_2, that is, where a hard metal is pushing a soft metal, the defect area is small. Carrying this example to the extreme, assume that the hard metal was steel and that the soft metal were a liquid, say water. It can be visualized that a very small defect would form because

Type 1 [illegible] Type 2 but the lowest K_1/K_2 ratio. It appears as the two kinds for Types 3, 4, and 5, the K_1/K_2 ratio is slightly above 1.00. This is momentarily understandable if one recognizes that part of the load registered by the tensile machine is due to the friction between the load and the cylinder wall. In the beginning the friction is greatest because there is more friction area. As the extension continues this area is reduced and consequently the friction is reduced, giving a lower reading for the second billet than the first.

Note also the very good agreement found in Types 3, 4, and 5 as to variation in K_1/K_2. This would give credence to the values obtained for the other types.

Table IV is a compilation of the extrusion pressures (K) for the metals used, depending upon whether it was the first or second billet out of the die. These values agree fairly well with published data, but as was stated earlier, so many other variables enter into the determination of K that before comparisons can be made, the complete picture must be analyzed as to temperature, lubrication, die geometry, and ram speed. Sufficient, however, is the fact that K did remain a constant for this series of experiments.

Referring again to the series of curves plotted in Figures 29 - 32, it will be noted that they are all similar to a modified S-curve. At the low values of K_1/K_2, that is, where a hard metal is pushing a soft metal, the defect area is small. Carrying this example to the extreme, assume that the hard metal was steel and that the soft metal were a liquid, say water. It can be visualized that a very small defect would form because

the water, under hydrostatic pressure, with negligible shear, would flow completely out of the die before the steel was extruded. It is true that as the steel was extruded it would not come out flat, but would have a defect. It is this aspect which would restrict one from obtaining a completely flat interface by variation of the K_1/K_2 alone. It is still necessary to preshape the billet. This point of view is merely academic, because in dealing with extrusion problems, the selection of K_1/K_2 is seldom allowed but rather pre-determined.

TABLE IV

EXTRUSION CONSTANTS (K)

METAL	EXTRUSION CONSTANTS (PSI)
Pure Lead (1st Billet)	6374
Pure Lead (2nd Billet)	6032
3% Antimony (1st Billet)	10163
3% Antimony (2nd Billet)	9347
10% Antimony (1st Billet)	11712
10% Antimony (2nd Billet)	11011

As the ratio of K_1/K_2 increases from this low value (less than 1) to values around unity, the curves increase until a maximum is reached which generally lies somewhere between $K_1/K_2 = 1.0$ and 2.0. Herein is

which generally lies somewhere between $E_1/E_2 = 1.0$ and 2.0. Herein is

As the ratio of K_1/K_2 increases from this low value (less than 1)

to values around unity, the curves increase until a maximum is reached

METAL	EXTRUSION CONSTRAINTS (psi)
Pure lead (Jet Billet)	6374
Pure lead (2nd Billet)	6032
3% Antimony (Jet Billet)	10163
3% Antimony (2nd Billet)	9347
10% Antimony (Jet Billet)	11712
10% Antimony (2nd Billet)	11021

TABLE IV

the water, under hydrostatic pressure, with negligible shear, would flow

completely out of the die before the steel was extruded. It is true that

as the steel was extruded it would not come out flat, but would have a

defect. It is this aspect which would restrict one from obtaining a

completely flat interface by variation of the K_1/K_2 alone. It is still

necessary to premanipe the billet. This point of view is merely academic,

because in dealing with extrusion problems, the selection of E_1/E_2 is

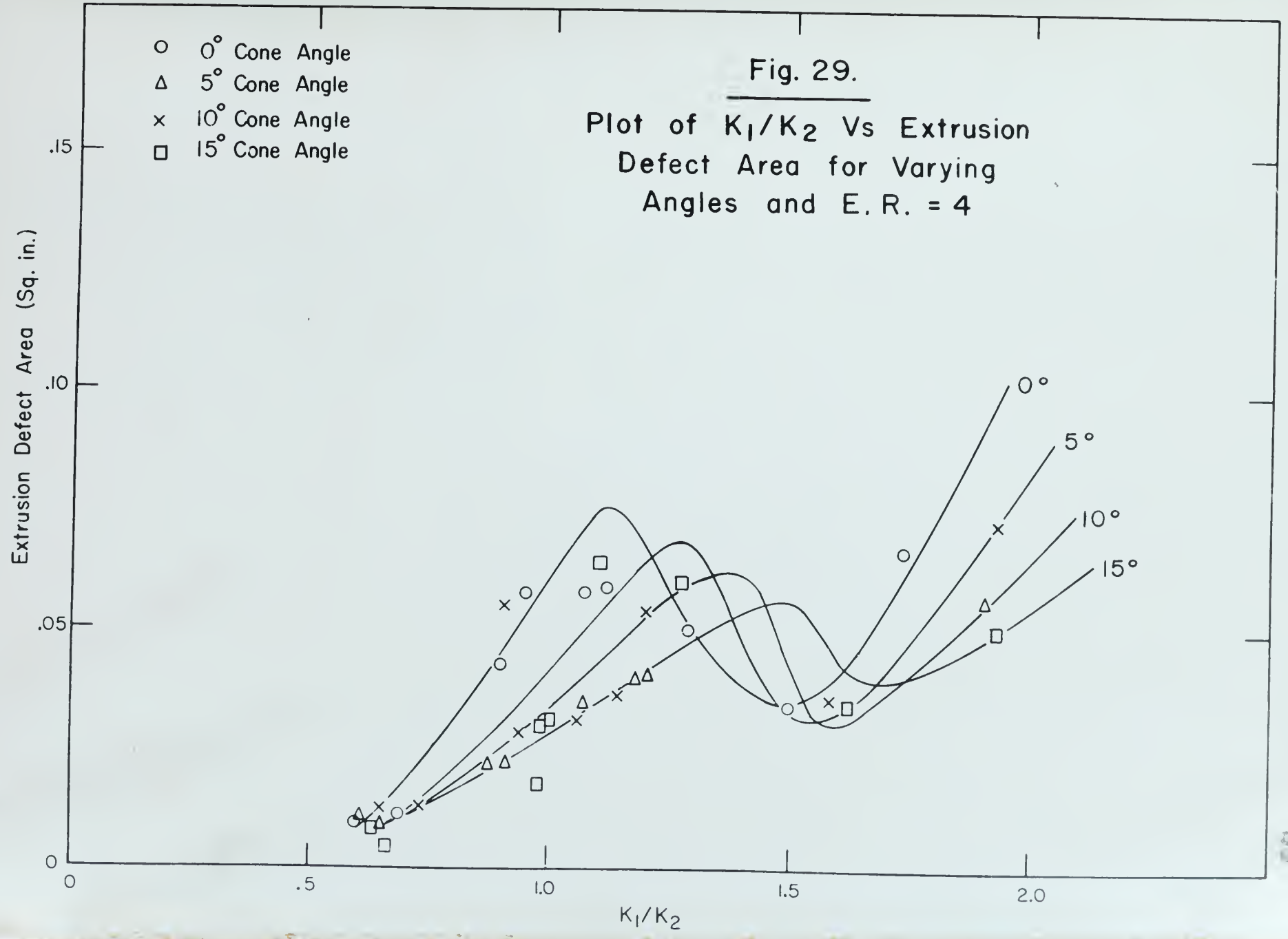
seldom allowed but rather pre-determined.

the situation where both metals are of the same hardness. As could be expected in this range, an increase in the extrusion ratio causes an increase in the defect area.

Any further increase in K_1/K_2 causes a sharp drop in the defect area which, up to this point, is the most significant aspect noticed. Increasing K_1/K_2 still further produces a minimum to the curve after which it again starts to climb and as far as these experiments were concerned, did not reach a plateau or reverse itself again.

The fact that these curves were not smoothly varying curves without maximums or minimums points up the strong dependence of the defect area on the K_1/K_2 value. For example, if one has a pre-determined K_1/K_2 and extrusion ratio, then one does not know where he might be in relation to the maximum or minimum without having one of these experimental curves available. Basic theory cannot, and does not predict these S-curves.

The minimum values reached were unquestionably noted and repeated themselves to the point of almost certainty. Again going to extreme situation, assume that water is pushing steel and it can be visualized that a large defect would form because again the water acting under hydraulic pressure will exert itself equally on the surface of the steel. As the steel flows out, the central mass is flowing faster than the edge mass and a large defect would develop. Thus, the large defect values found for high K_1/K_2 are understandable.


○ 0° Cone Angle
△ 5° Cone Angle
× 10° Cone Angle
□ 15° Cone Angle
Fig. 29.
Plot of K_1/K_2 Vs Extrusion Defect Area for Varying Angles and E. R. = 4
Extrusion Defect Area (Sq. in.)
.15
.10
.05
0
0
.5
1.0
1.5
2.0
K_1/K_2
0°
5°
10°
15°

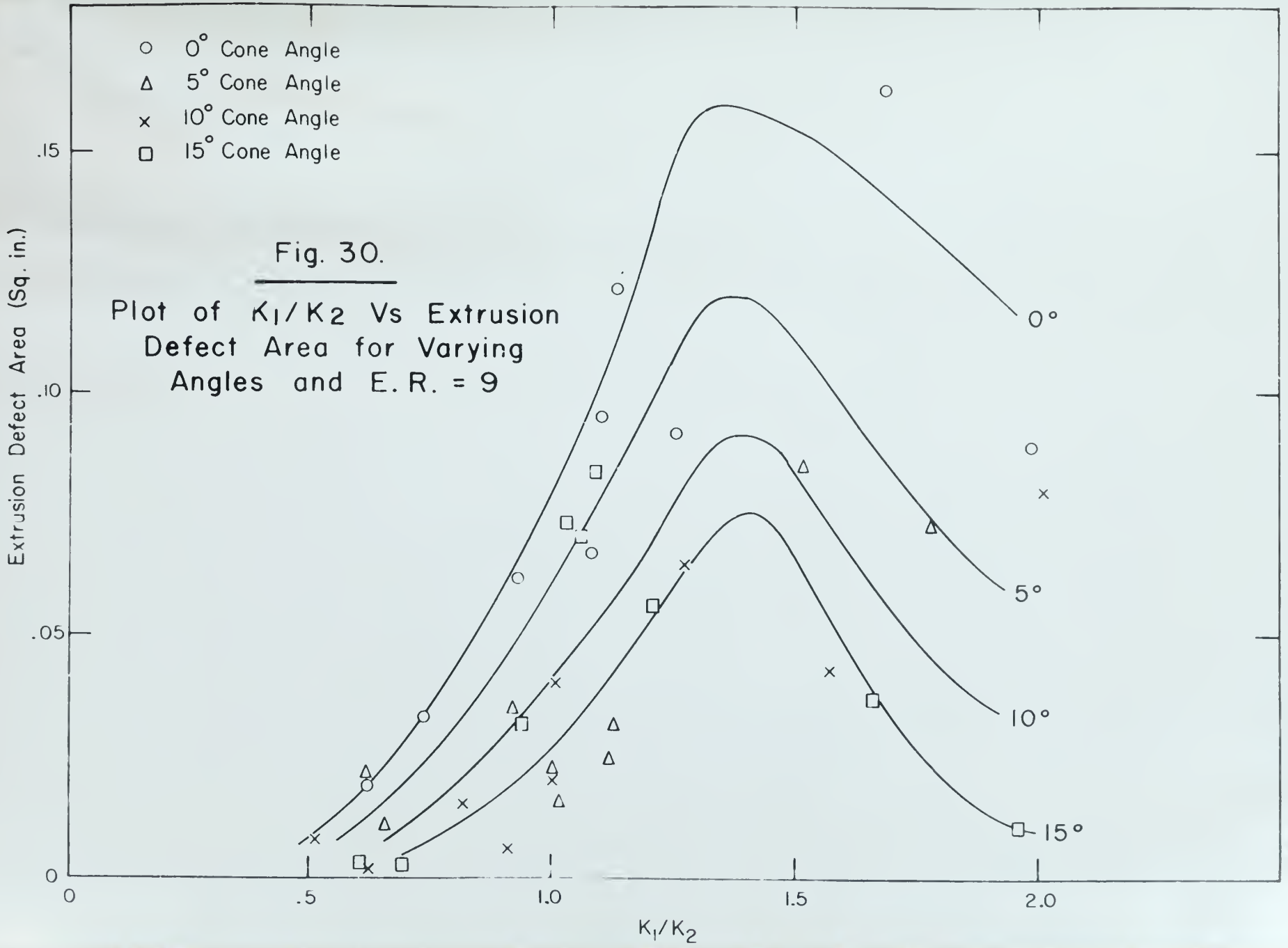


Fig. 30.

Plot of K_1/K_2 Vs Extrusion Defect Area for Varying Angles and E.R. = 9

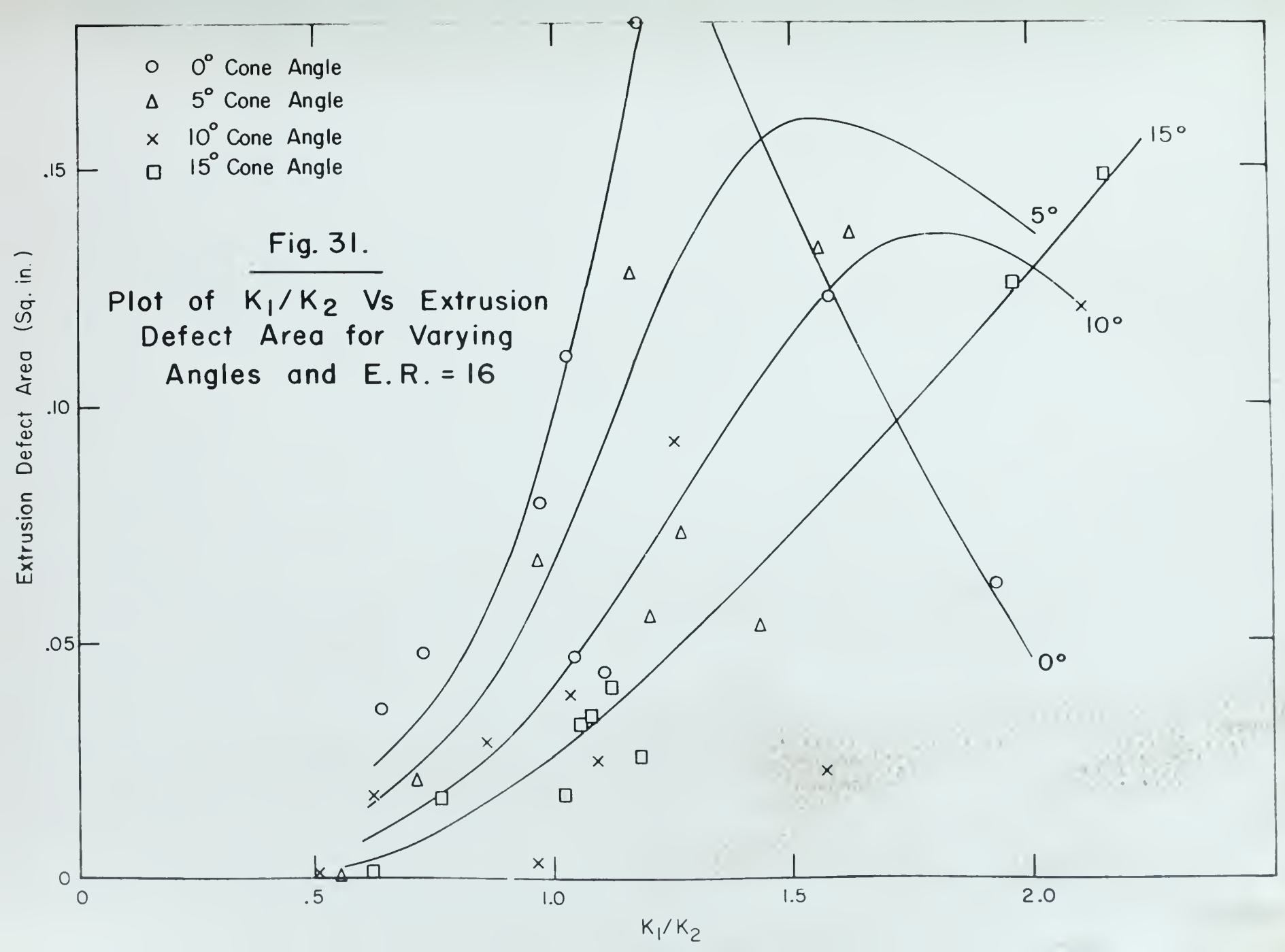
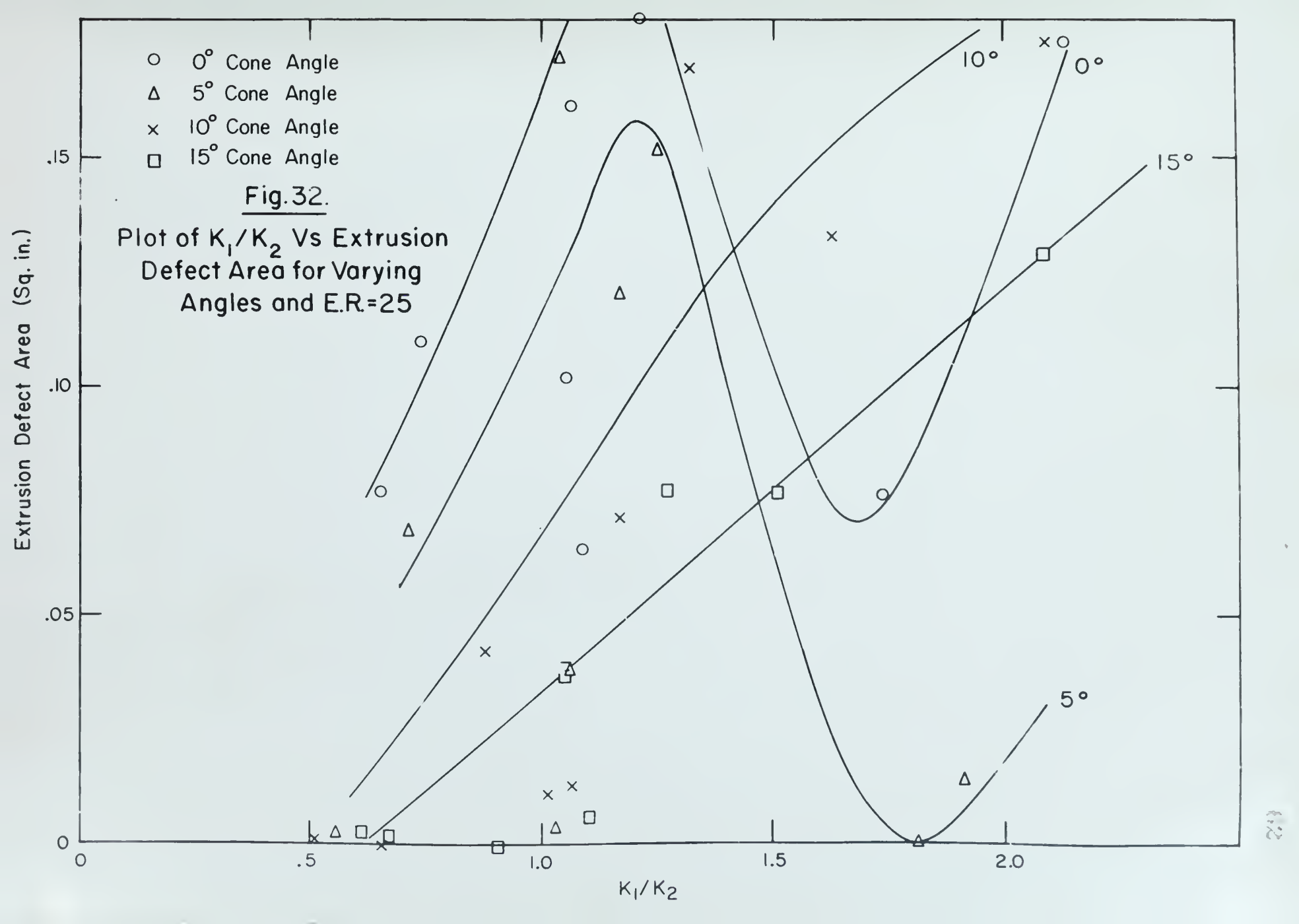


Fig. 31.

Plot of K_1/K_2 Vs Extrusion Defect Area for Varying Angles and E.R. = 16


○ 0° Cone Angle
△ 5° Cone Angle
× 10° Cone Angle
□ 15° Cone Angle
Fig. 32.
Plot of K_1/K_2 Vs Extrusion Defect Area for Varying Angles and E.R.=25
Extrusion Defect Area (Sq. in.)
.15
.10
.05
0
0
.5
1.0
1.5
2.0
K_1/K_2
10°
0°
15°
5°

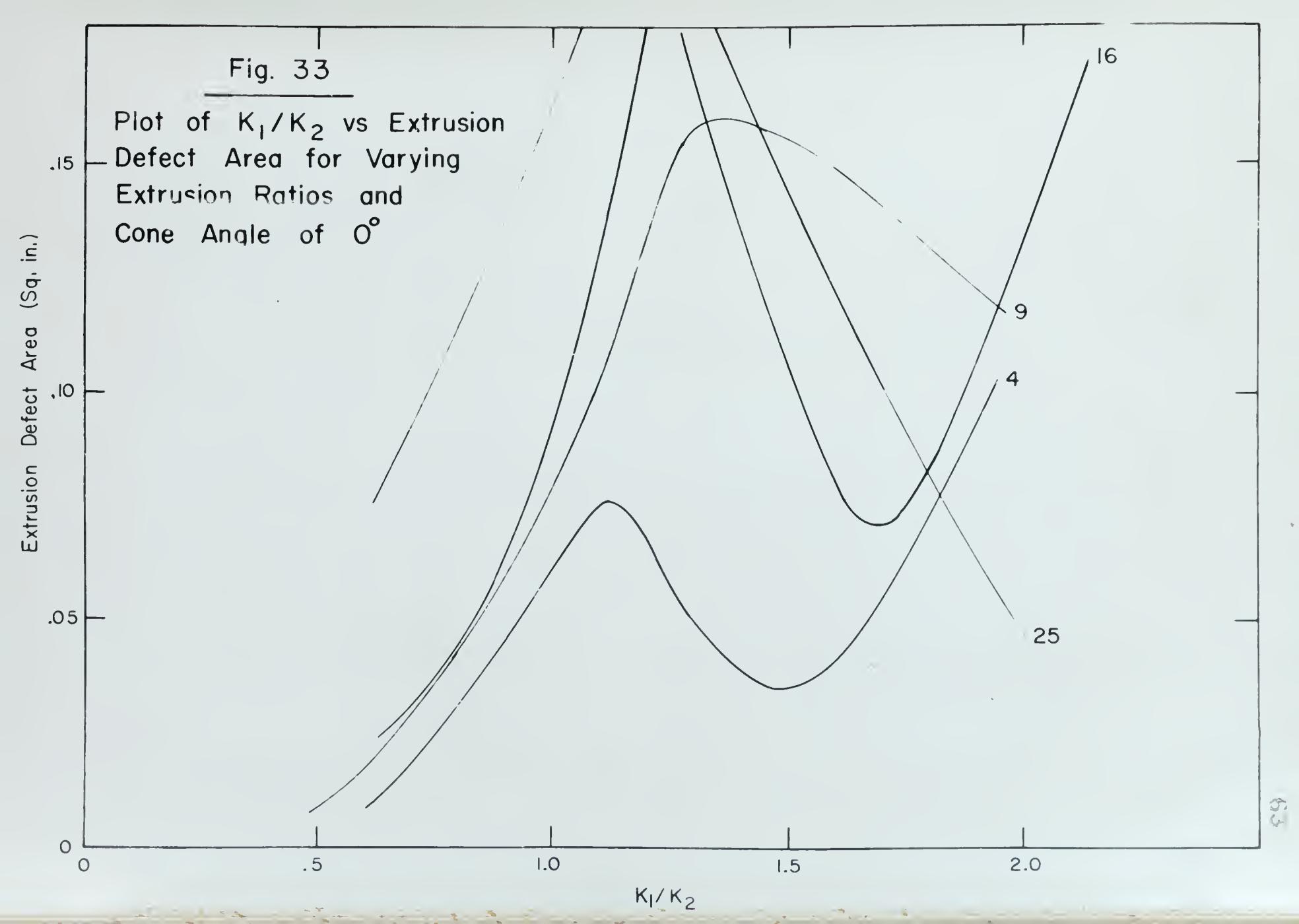


Fig. 33
Plot of K_1/K_2 vs Extrusion Defect Area for Varying Extrusion Ratios and Cone Angle of 0°
Extrusion Defect Area (Sq. in.)
0
.05
.10
.15
0
.5
1.0
1.5
2.0
K_1/K_2
16
9
4
25

Fig. 34

Plot of K_1/K_2 vs Extrusion Defect Area for Varying Extrusion Ratios and Cone Angle of 5°

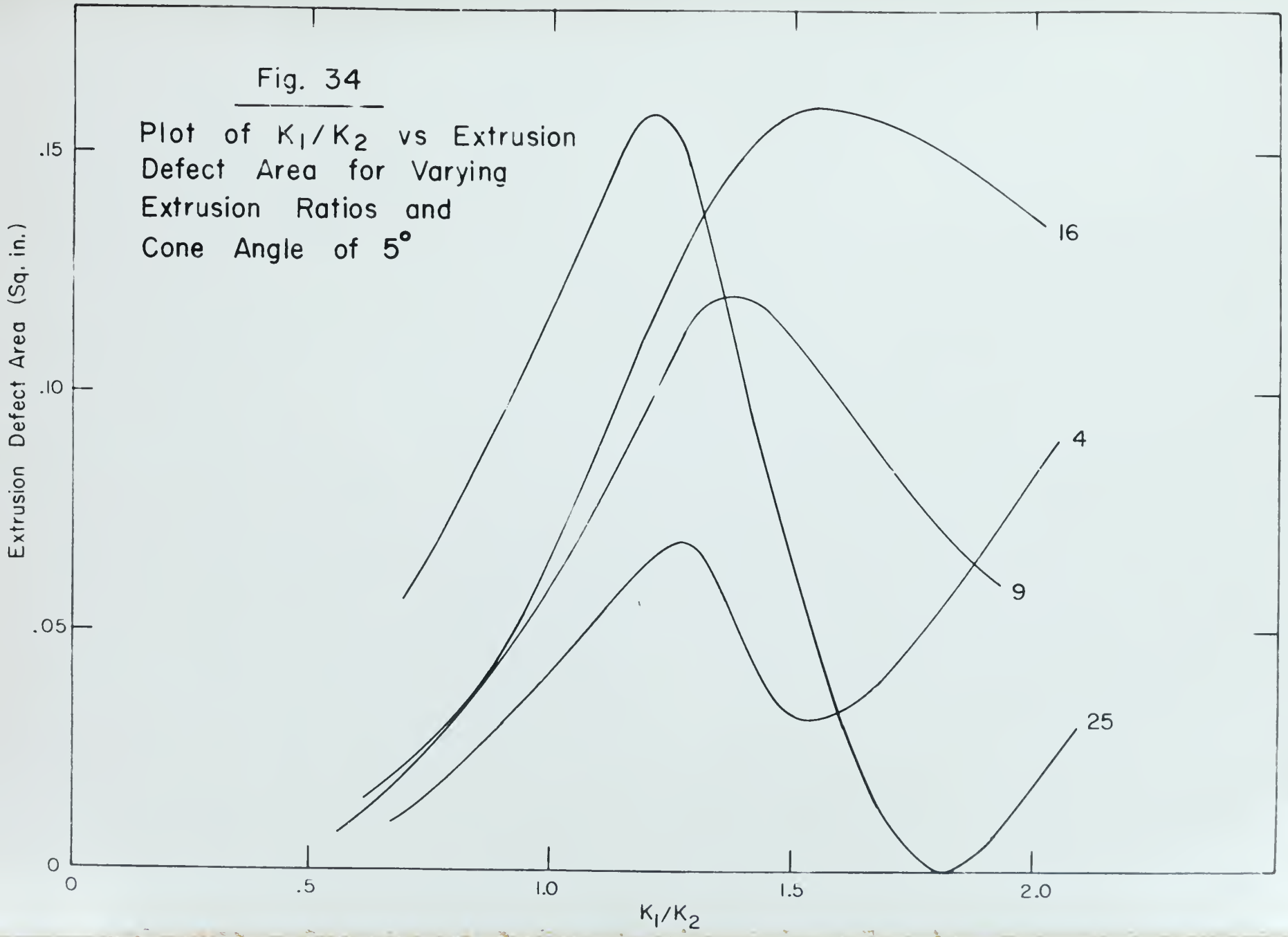


Fig. 35

Plot of K_1 / K_2 vs Extrusion Defect Area for Varying Extrusion Ratios and Cone Angle of 10°

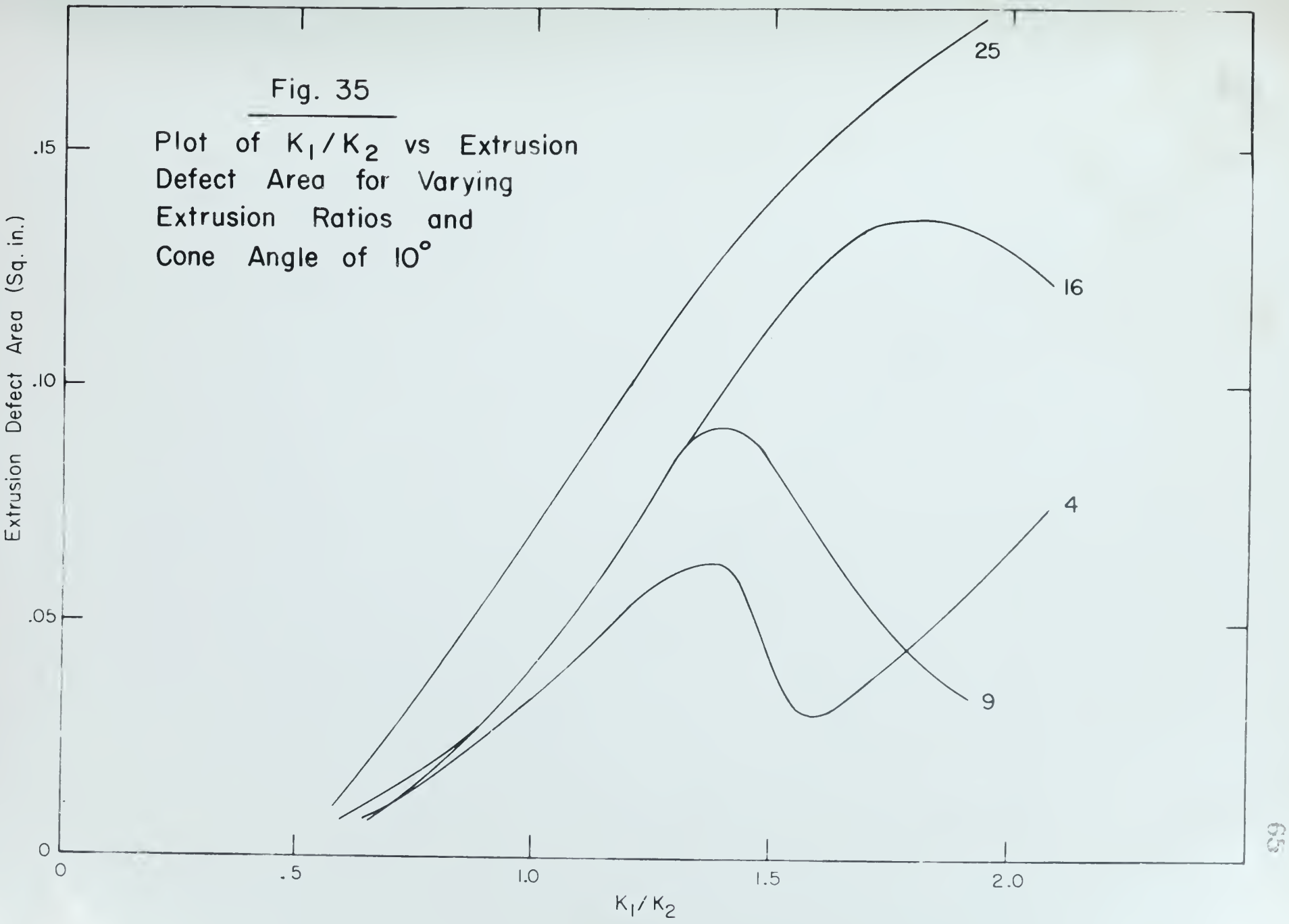
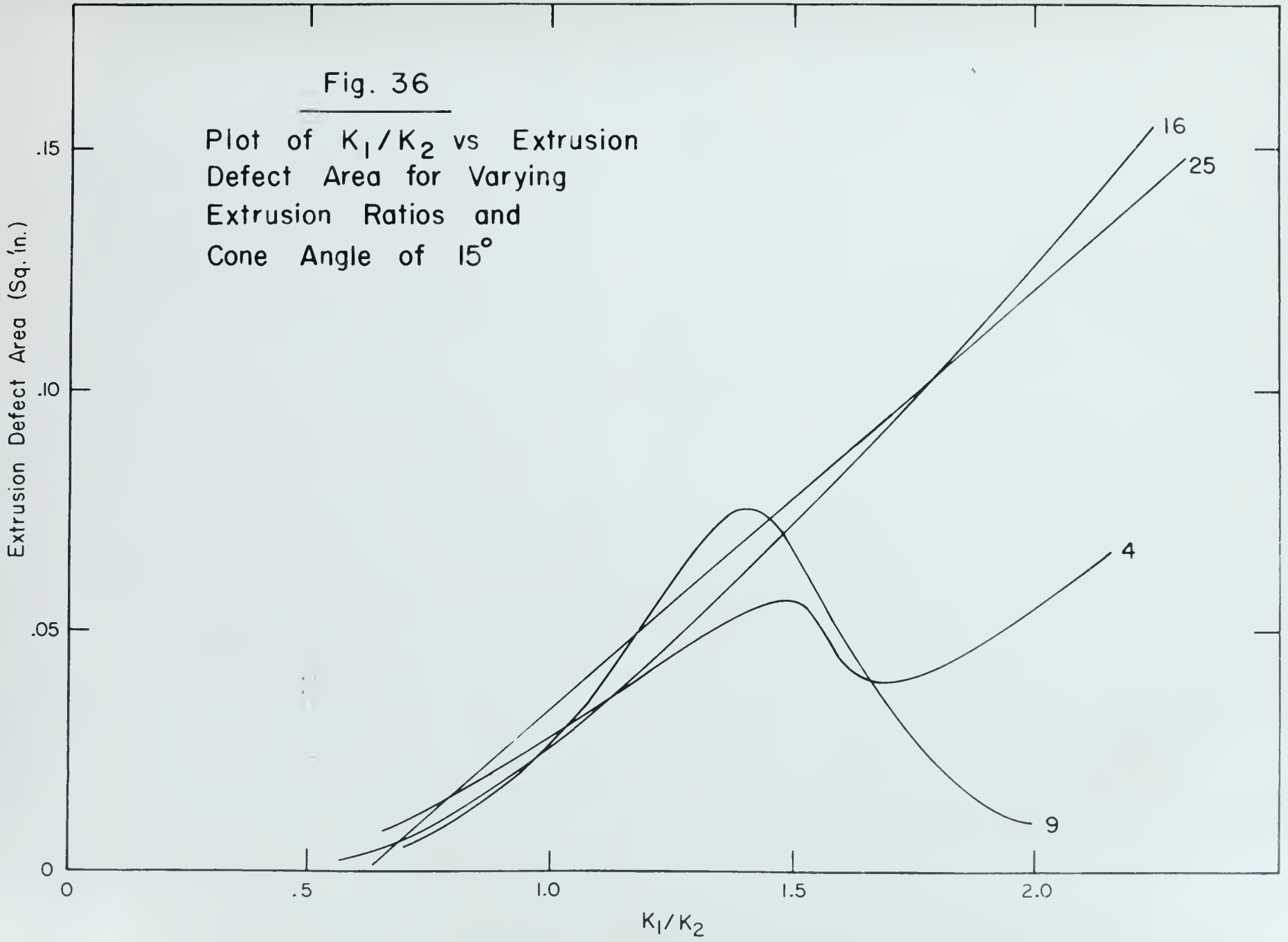


Fig. 36

Plot of K_1/K_2 vs Extrusion Defect Area for Varying Extrusion Ratios and Cone Angle of 15°



C. Effect of Variation of Cone Angle

If attention is now directed to the variation of the defect area with cone angle it can be seen that no clear cut rule can be laid down. Generally, when the cone angle is increased from the flat interface (0° cone angle) the size of the defect decreases, but there are definite tendencies which show that for particular ratios of K_1/K_2 and extrusion ratios, increasing the cone angle actually increases the defect area. When the ratio of K_1/K_2 is around unity then the general rule holds. Beyond a value corresponding to the peaks, variation in cone angle is completely dependent upon the relative position of the maximum and minimum of the various S-curves.

In order to graphically illustrate the dependence of defect area on both K_1/K_2 and cone angle, Figures 37 - 40 have been plotted in a three-dimensional diagram showing the contours obtained for the various extrusion ratios.

In attempting to find some justification for the peak values of defect area as the K_1/K_2 ratio exceeds unity and then suddenly drops, it becomes paramount to again question the method by which the defect area was measured. This problem manifested itself from the beginning because no clear cut definition of the defect was available. In utilizing the area as finally selected, it was felt that this area was certainly as good as any other parameter which was available. It may be that the characteristic S-curve is a direct result of this selection and that no theoretical analysis can explain these curves. It is of interest to note that if the area acbf of Figure 15 is used as the defect area, the same type of curves are obtained. This fact, in some small way, substantiates the results found by using the parameter as chosen.

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FIGURE 37.

THREE-DIMENSIONAL PLOT OF K_1/K_2 VS CONE ANGLE VS EXTRUSION DEFECT AREA

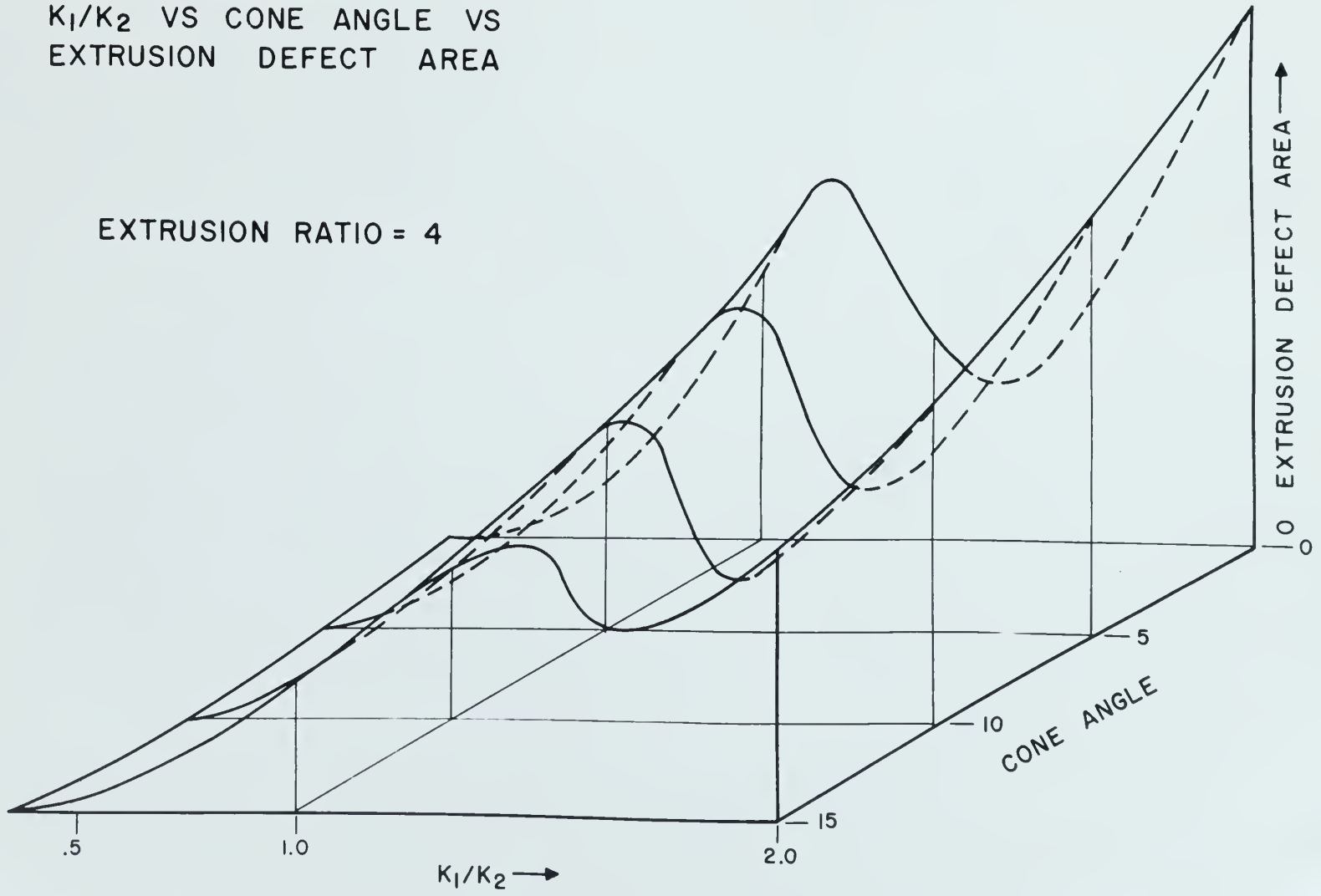


FIGURE 38.

THREE-DIMENSIONAL PLOT OF K_1/K_2 VS CONE ANGLE VS EXTRUSION DEFECT AREA

EXTRUSION RATIO = 9

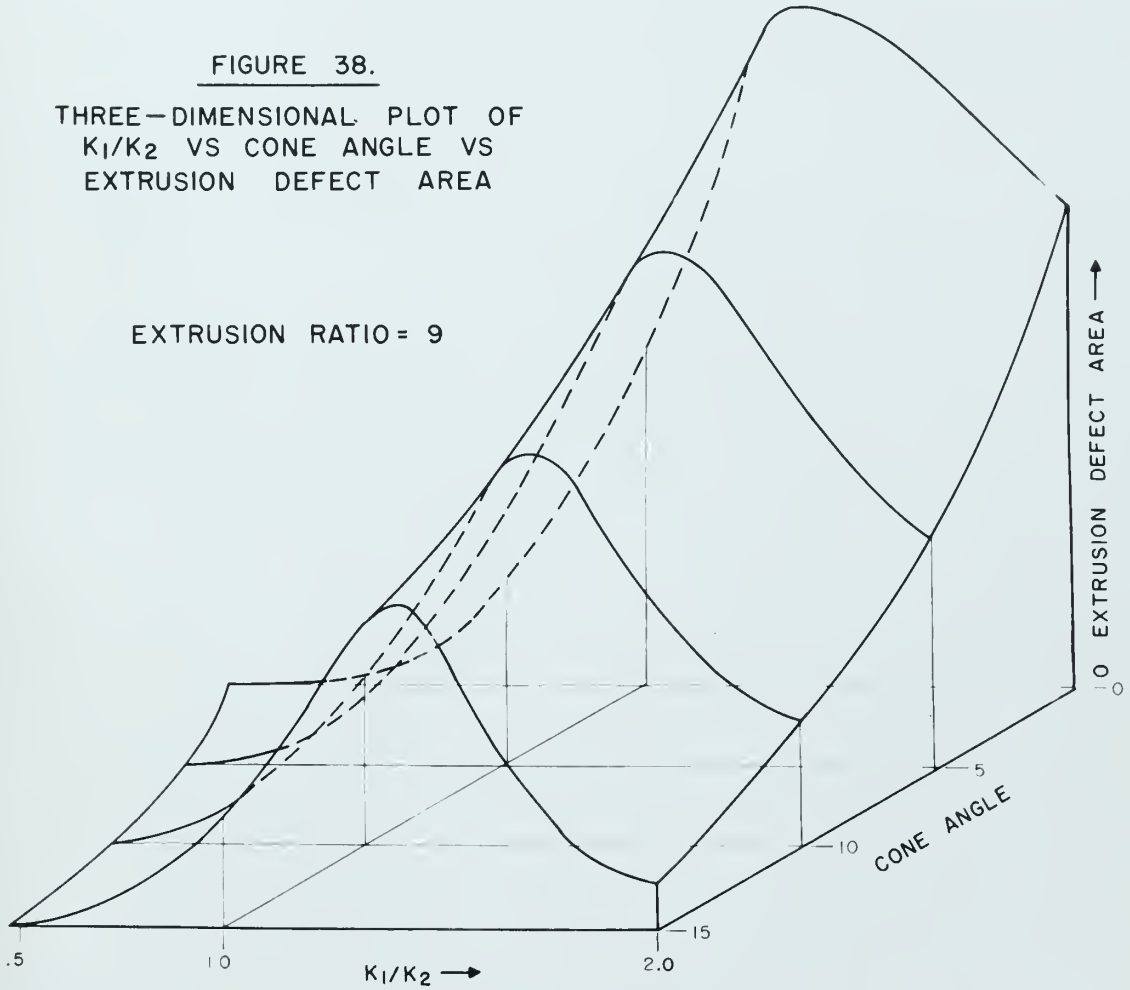


FIGURE 39.

THREE-DIMENSIONAL PLOT OF K_1/K_2 VS CONE ANGLE VS EXTRUSION DEFECT AREA

EXTRUSION RATIO = 16

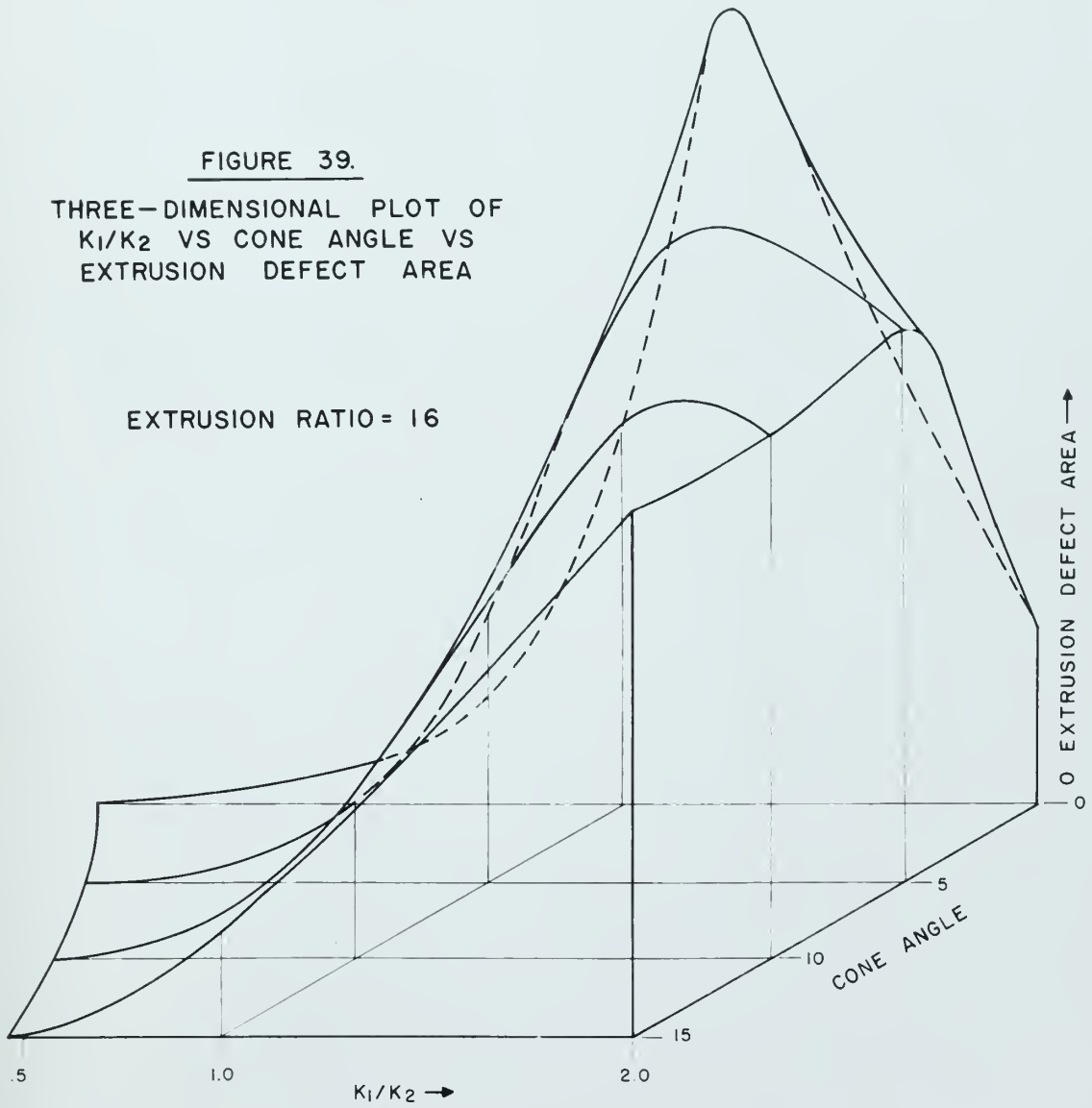
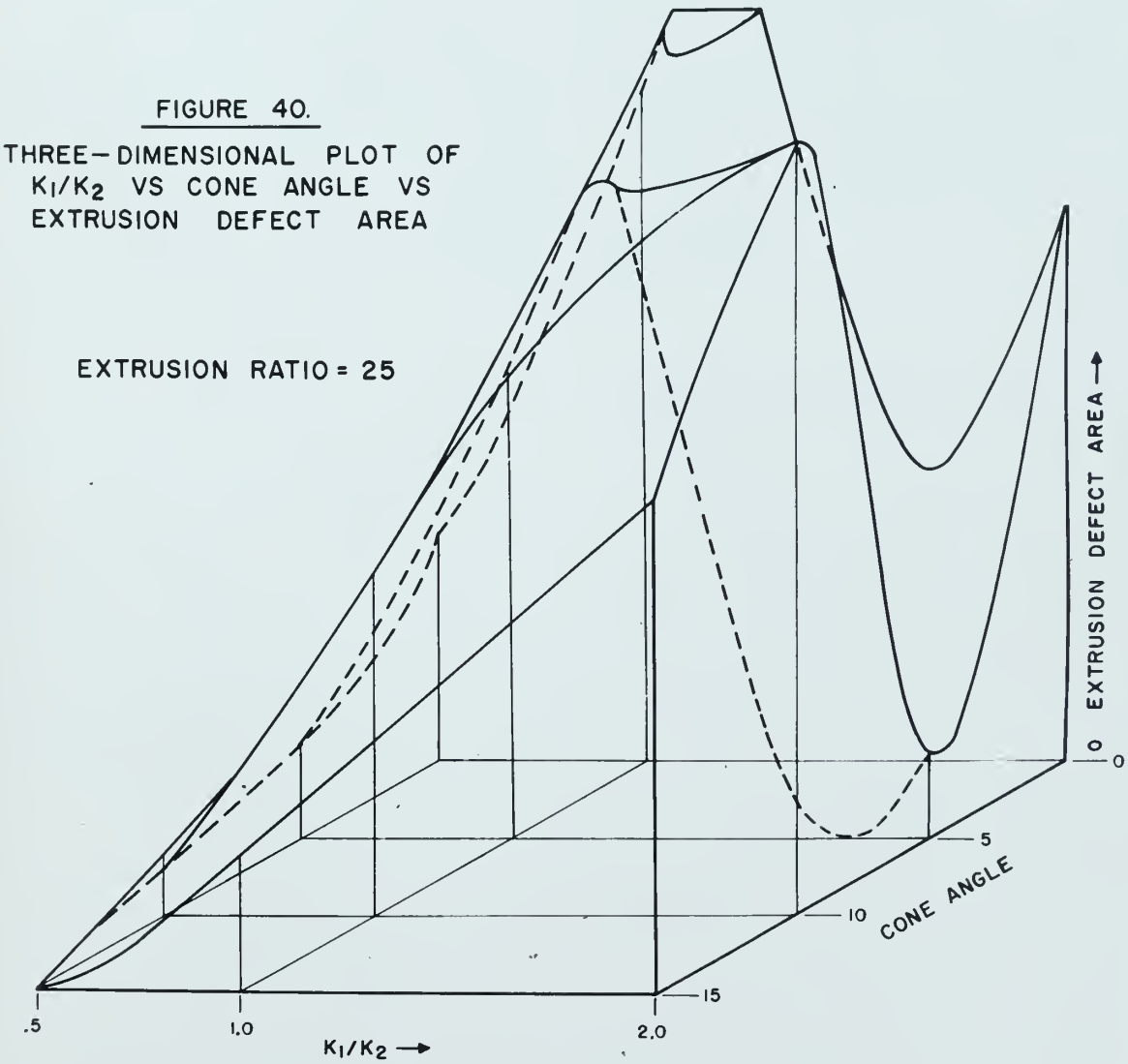


FIGURE 40.

THREE-DIMENSIONAL PLOT OF K_1/K_2 VS CONE ANGLE VS EXTRUSION DEFECT AREA

EXTRUSION RATIO = 25



D. Formation of Voids

In 32 cases out of the 144 samples tested, voids were formed between the two metals after extrusion. Almost without fail the K_1/K_2 ratio was very low when the void formed. This is easily understood when it is realized that a hard metal is pushing the soft metal. As the interface passes through the die, the rear defect formed in the soft metal continues to increase by tailing back along the outer edge. The harder metal having a higher shear stress is incapable of keeping up with the faster moving soft metal in the center. As a result a void is formed.

Tabulated below is the result of void formation:

TABLE V

TYPE*	NUMBER OF SAMPLES WHERE VOID FORMED
A (Low K_1/K_2)	11
B	8
C	6
D	2
E	2
F	2
G	0
H	0
I (High K_1/K_2)	0

*See Table III

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VII. CONCLUSIONS

Before any conclusions can be reached it should be borne in mind that 144 test samples were investigated and that of these 144 samples no two were the same. Any analysis which might be based on the numerical data obtained from any one sample is very doubtful. Any curve drawn using as its basis the data from one sample is extremely doubtful. It is for this reason that great liberty was taken by the author in arriving at the curves. Many points fell entirely outside the range of reasonableness and were just discounted altogether. Thus, the conclusions that follow are based solely on the trends that this experimenter thought were evident. Another person, in viewing this data, might very well arrive at completely opposite views.

Based on the data found in this experiment and the interpretation placed thereon, certain conclusions can be reached.

A. To a certain degree, interfaces resulting from extruding two metals of differing stiffnesses can be predicted. If one knows K_1/K_2 and the extrusion ratio then it should be possible to select a preshaped cone angle which would result in the flattest interface obtainable under those circumstances. This interface will not necessarily be completely flat.

B. Extremely small defects result when K_1/K_2 is small, regardless of the extrusion ratio. However, the undesirable result of voids is prevalent at small K_1/K_2 ratios which means that little or no bonding would result at the interface. If bonding is important, then some means should be used to prevent extrusions at low K_1/K_2 ratios. This might be accomplished by the use of a buffer plate which has a stiffness

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intermediate between the two metals. Selection of this buffer material would have to be based on its nuclear as well as its mechanical properties.

C. Experimental determination of the S-curves would be very beneficial in determining the cone angle which should be used for obtaining flat interfaces.

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VIII. RECOMMENDATIONS

A. Extension of Investigation

1. It is recommended that further study be made at cone angles in excess of the 15° tried in this report. Each particular group of experiments should be carried to the point where the defect area becomes negative, that is, completely reverses itself.

2. It is recommended that, if this experiment is continued, each particular test be run at least three times in order to minimize the probable error. One great problem in extrusions is the fact that it is not an exact science due to the pronounced effect each of the many variables can play on the final result and the inability to precisely control these variables. The only solution to a situation of this type is to repeat the particular test enough times so as to minimize the effect of the variables.

B. Double Extrusion

It is recommended that the possibility of arriving at a flat interface by the use of double extrusion be investigated further, utilizing the apparatus for this experiment. The first extrusion should be done at extrusion ratios slightly over one and the second extrusion should be run at varying extrusion ratios in order to determine just what combination will result in a flat interface.

C. Buffer Plates

It is recommended that the idea of using a metal of intermediate stiffness between two metals where K_1/K_2 is small be investigated in order to determine if formation of voids can be eliminated completely.

VIII. RECOMMENDATIONS

A. Extension of Investigation

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It is recommended that the idea of using a metal of intermediate stiffness between two metals where K_f/E_f is small be investigated in order to determine if formation of voids can be eliminated completely.

APPENDIX A

1. Detailed Drawings of Apparatus

2. Photographs of Extruded Samples (Figures A-6 to A-21)

Each sheet of photographs contains those samples in which the extrusion ratio and cone angle remained fixed. Only the type of metal changed. See Table I for description of sample.

Arrow at top of sheet indicates direction of extrusion.

Note: Samples #55 and #144 were inadvertently placed in the opposite direction when photographed and consequently their direction of extrusion is opposite to that indicated.

APPENDIX A

1. Detailed Drawings of Apparatus

2. Photographs of Extruded Samples (Figures A-4 to A-21)

Each sheet of photographs contains three samples in which the extrusion ratio and cone angle remained fixed. Only the type of metal changed. See Table I for description of sample.

Arrow at top of sheet indicates direction of extrusion.

Note: Samples #55 and #64 were inadvertently placed in the opposite direction when photographed and consequently their direction of extrusion is opposite to that indicated.

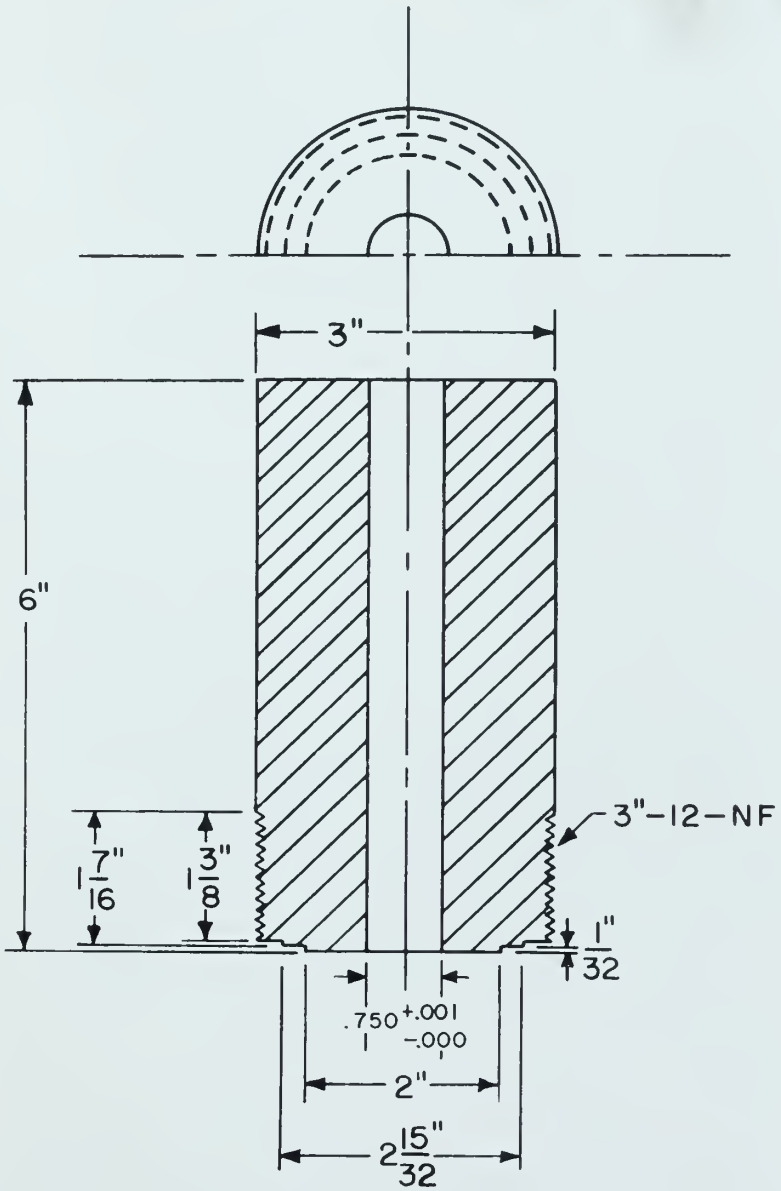
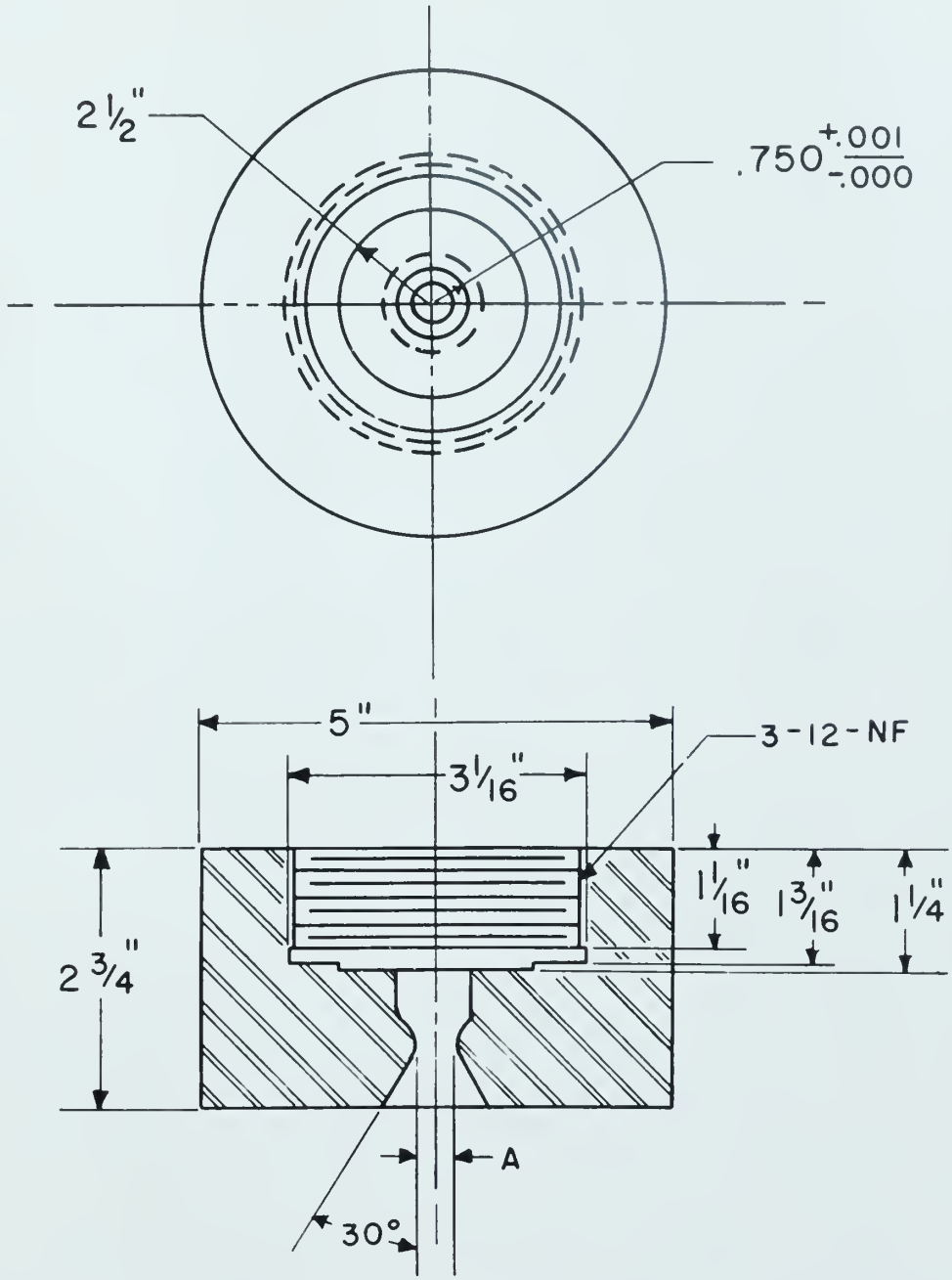


FIGURE A-1

Extrusion Cylinder



A	.375	.250	.1875	.150

Fig. A-2. Extrusion Dies

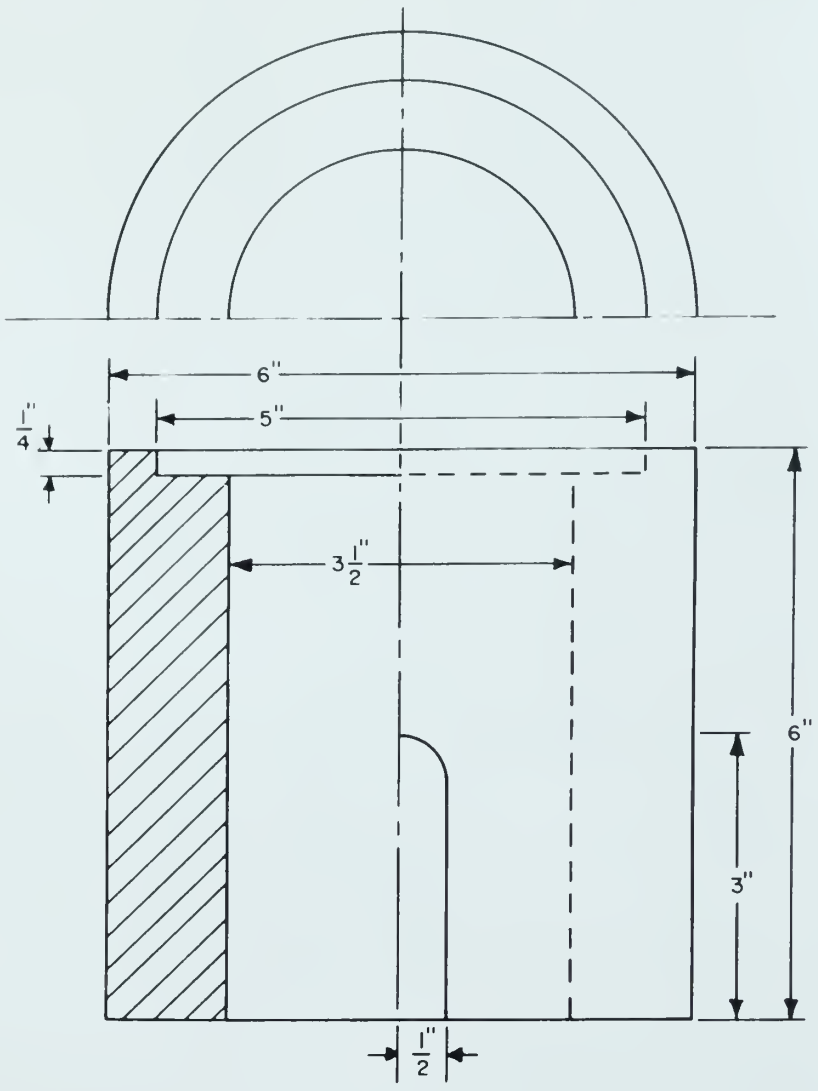


FIGURE A-3

Extrusion Stand

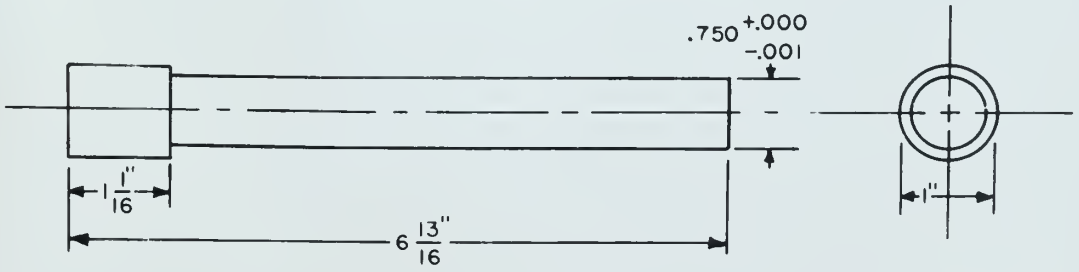


FIGURE A-4

Extrusion Ram

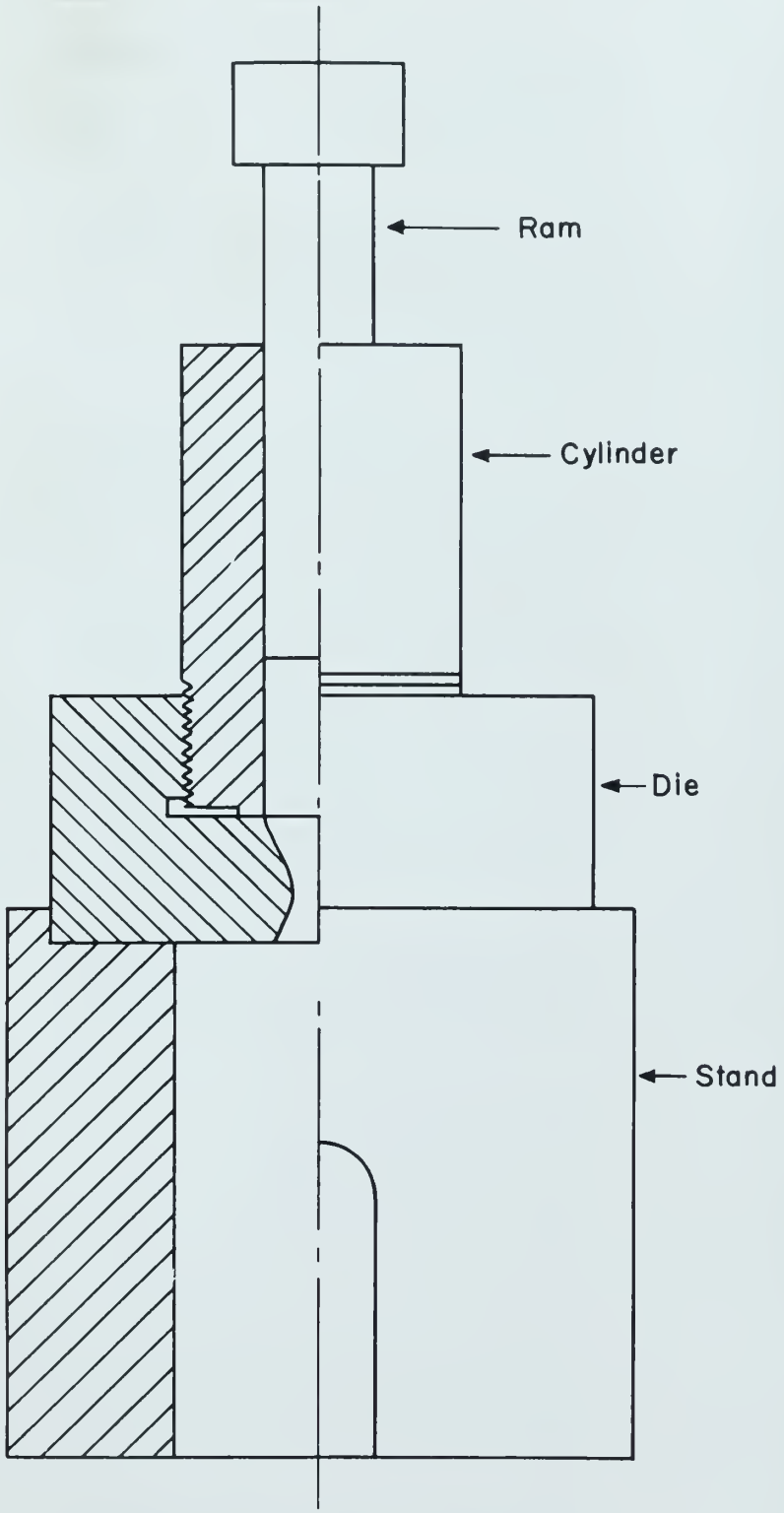


FIGURE A-5

Assembly of Extrusion Apparatus

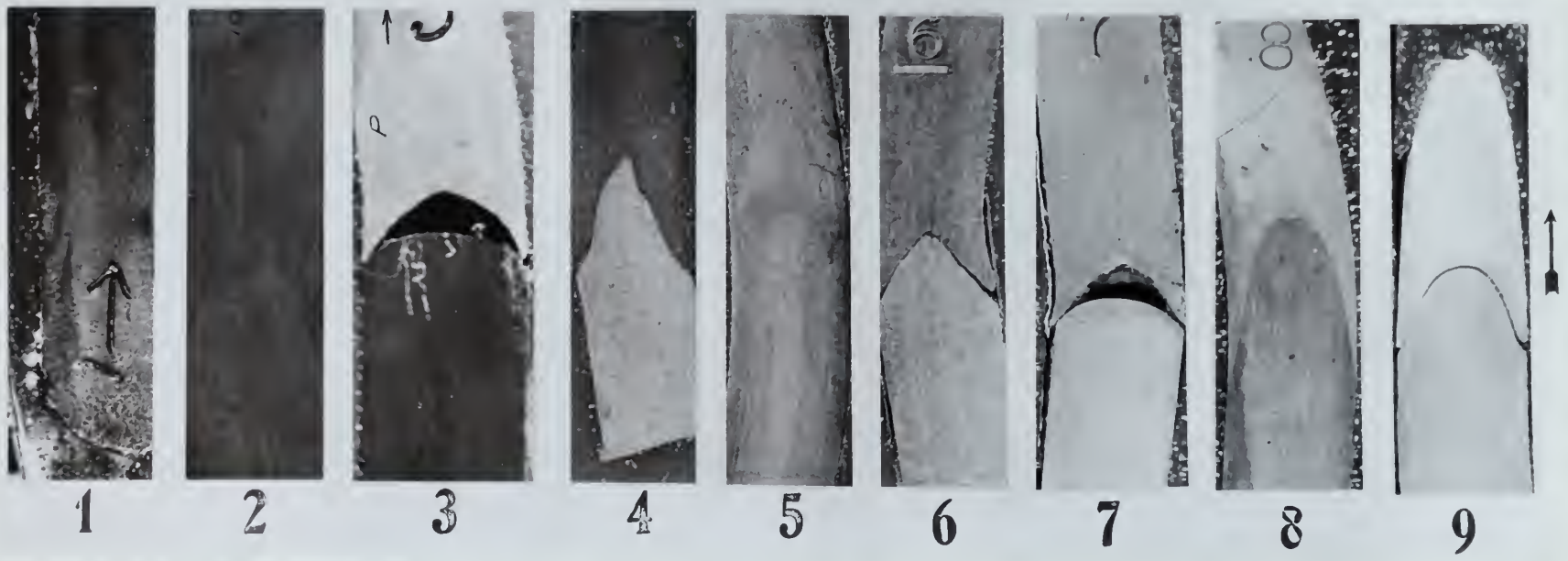


Figure A-6 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 4

Figure V-9 - Photographs of Combustion Bomb Bullets that Exploded Showing Internal Structure.

Explosion date = 1

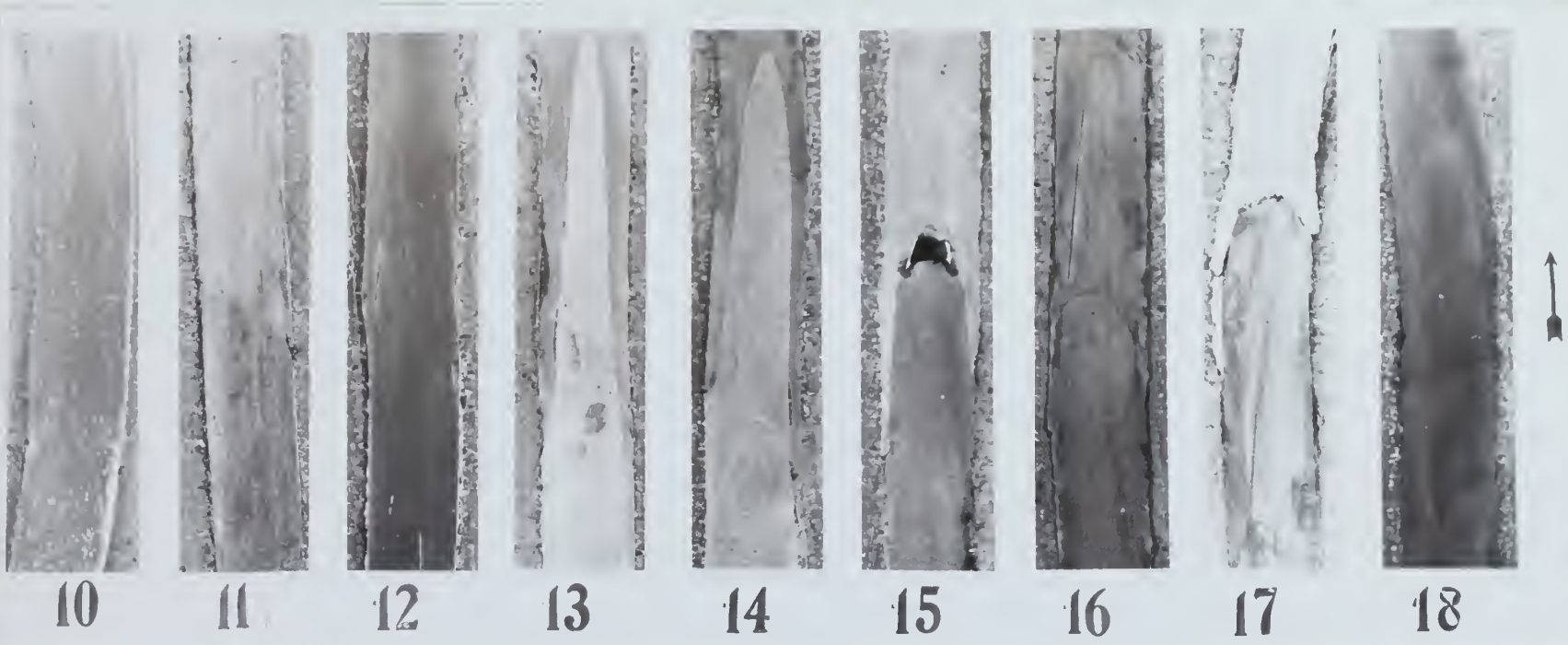


Figure A-7 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 9

Figure 4-1 - Hypothetical Compound Dilution Curve Showing Method of Determining Extinction Ratio

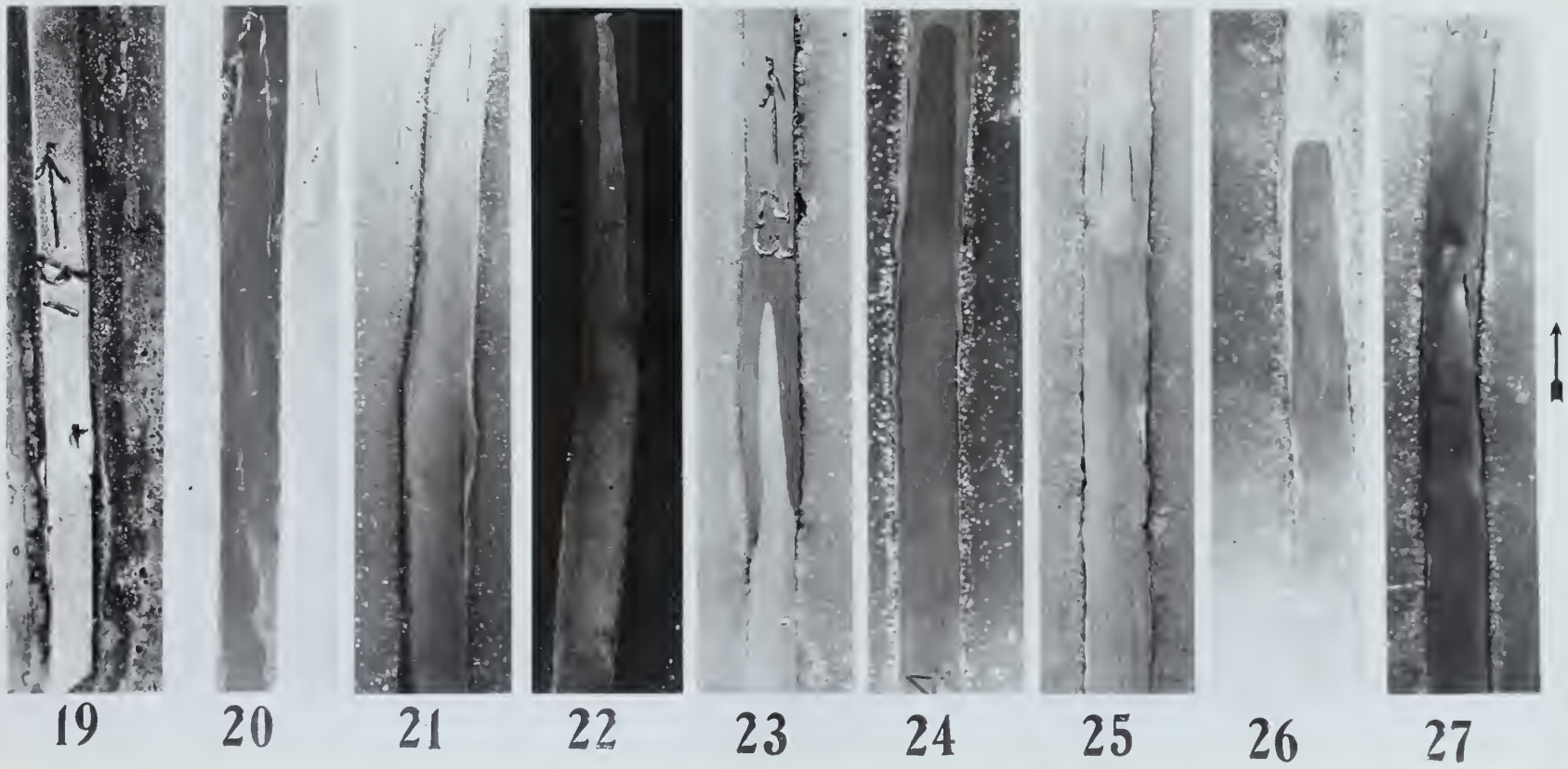


Figure A-8 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 16

Figure V-9 - Hypothesis of conditions to experiment "success"

Where: Ratio = IQ

Ql = eight mental tasks with Ratio level greater than 1.0

Q2 = eight mental tasks with Ratio level less than 1.0

Figure A-9 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 25

Figure 4-7 - Experimental and computed test stress versus motion sprung mass.

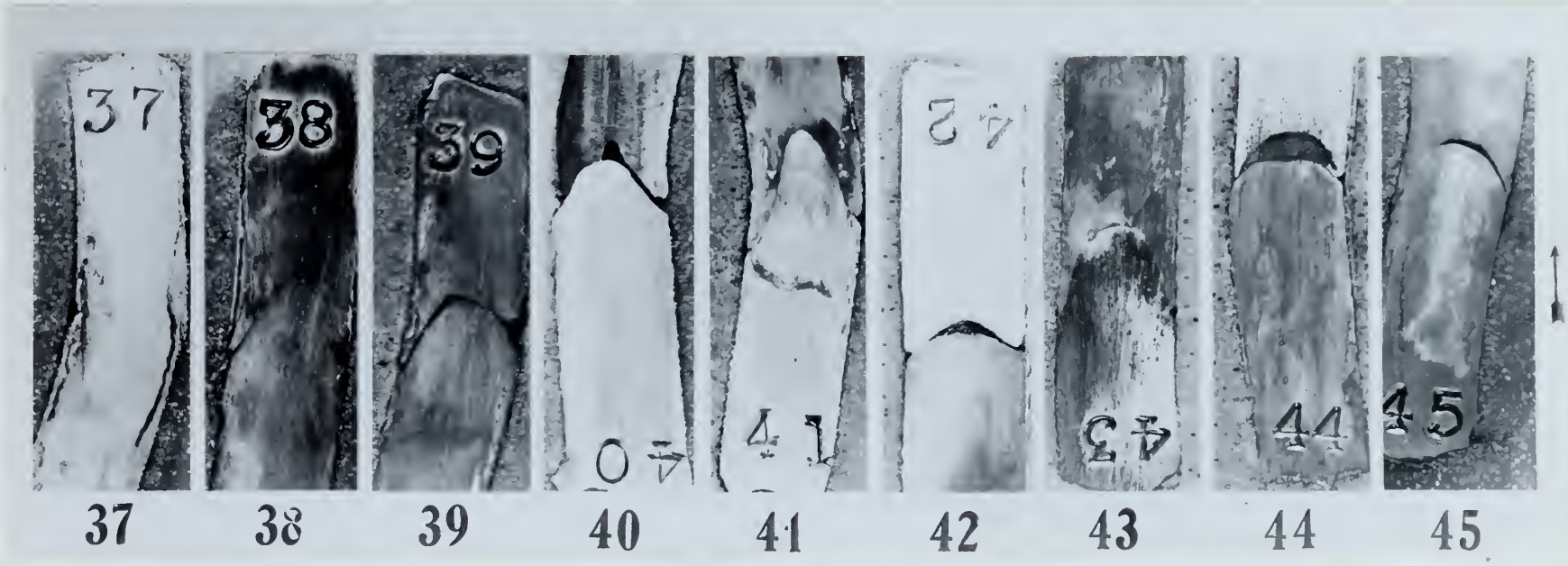


Figure A-10 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 4

Figure 7-10 - Hypothesis of Compound to Experimental Data

Retardation Rate = μ

"Control Limits" are plotted by multiplying the standard deviation of the experimental data by the appropriate "t" value.

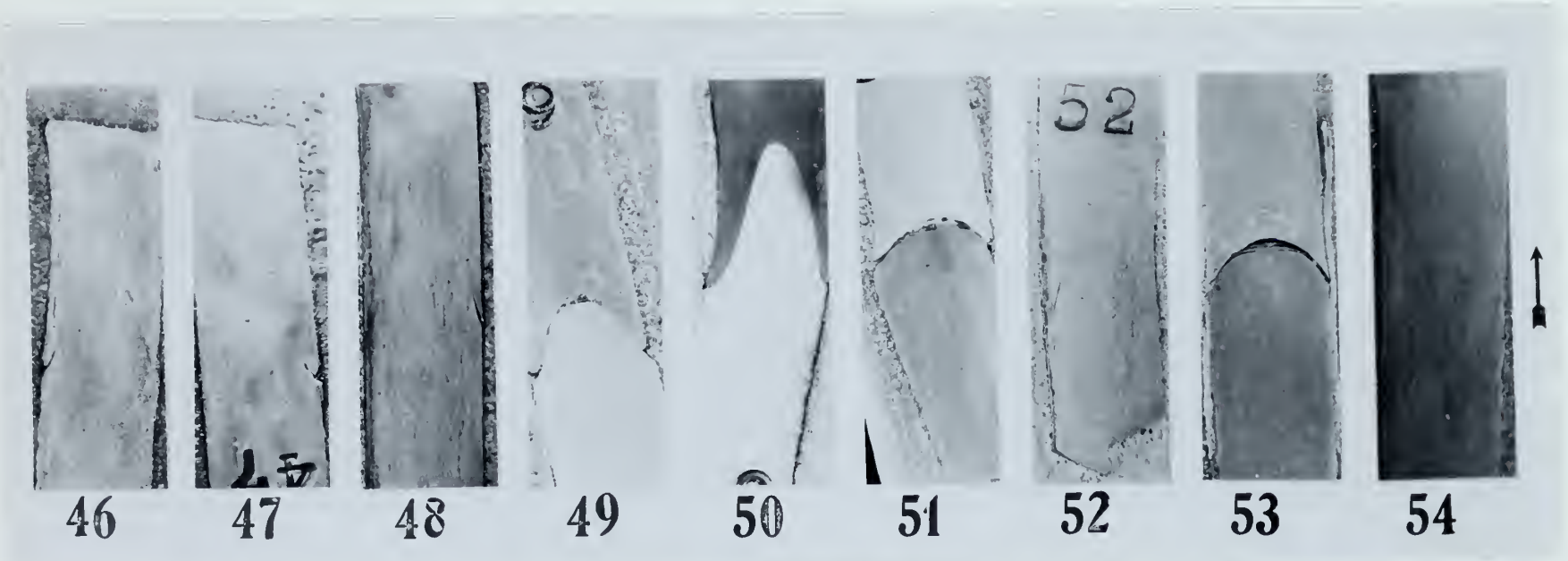


Figure A-11 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 4

Table V-II - Impact Energy of Concrete Test Bitten Tube Specimen Showing Tensile Failure.

Specimen Ratio = 1

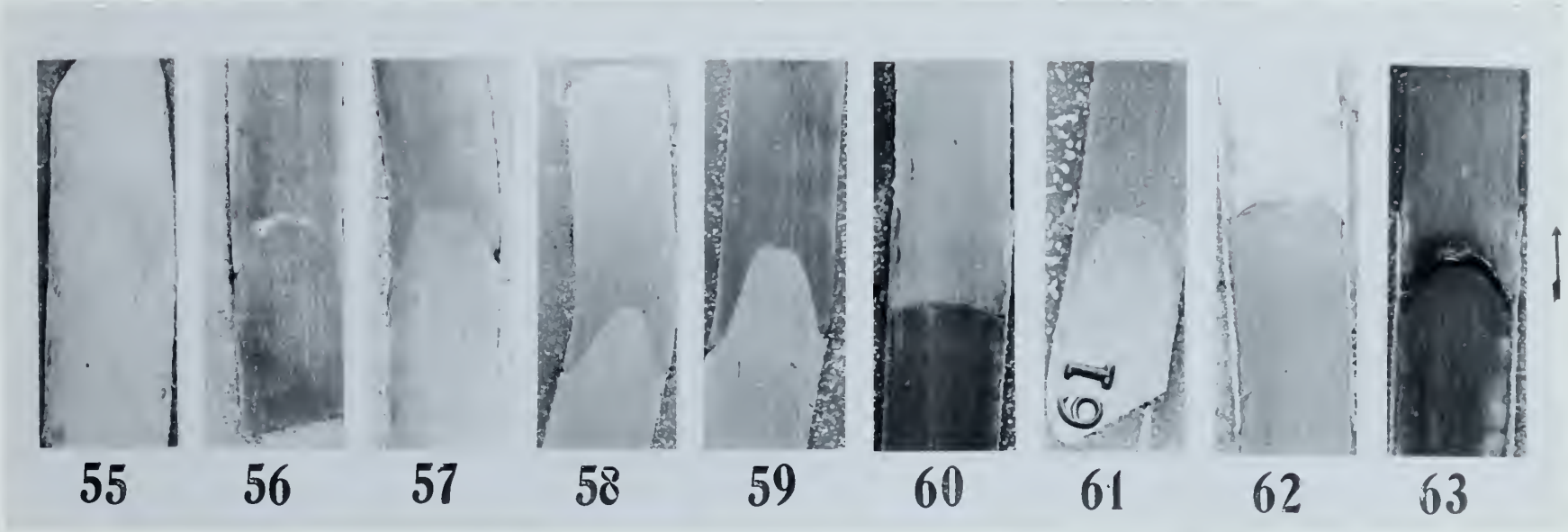


Figure A-12 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 4

Figure 4-15 - Liquefied natural gas vaporized to ambient temperature.

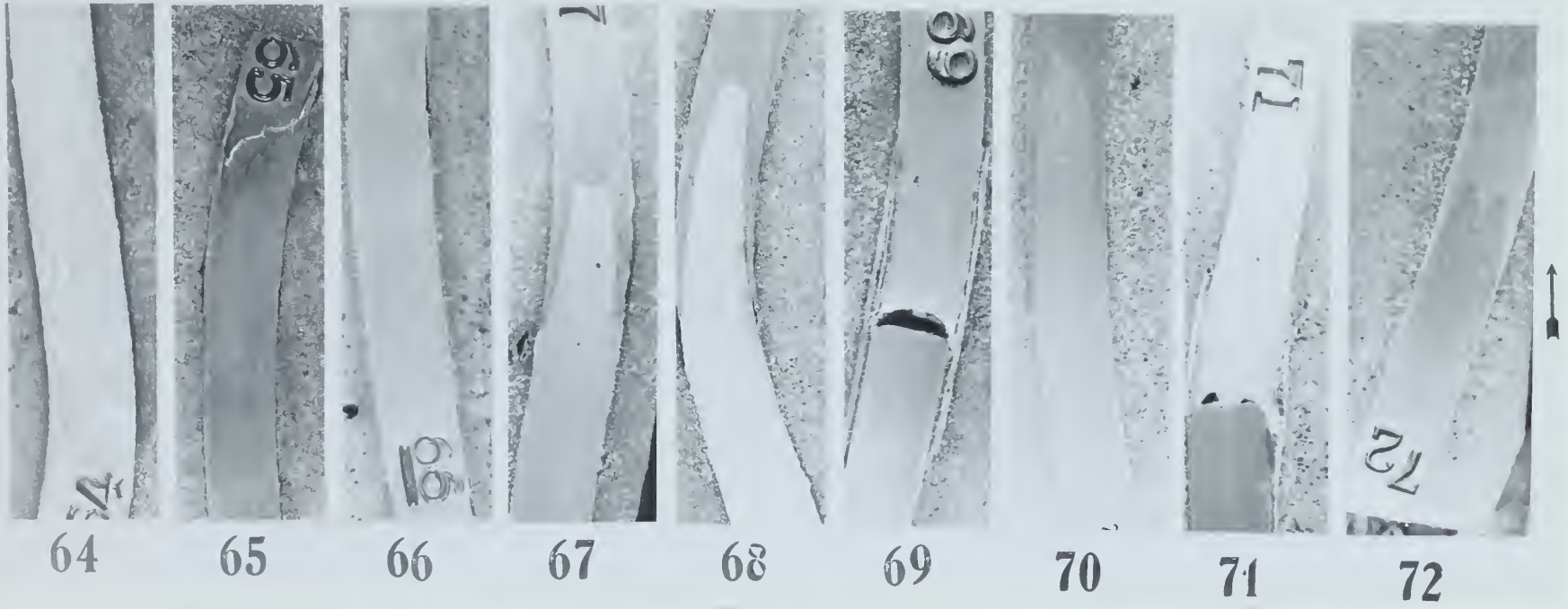


Figure A-13 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 9

Tabela V-13 - Morfologia do Complexo Tubo Ovário Glândula Nidamental Secundária.

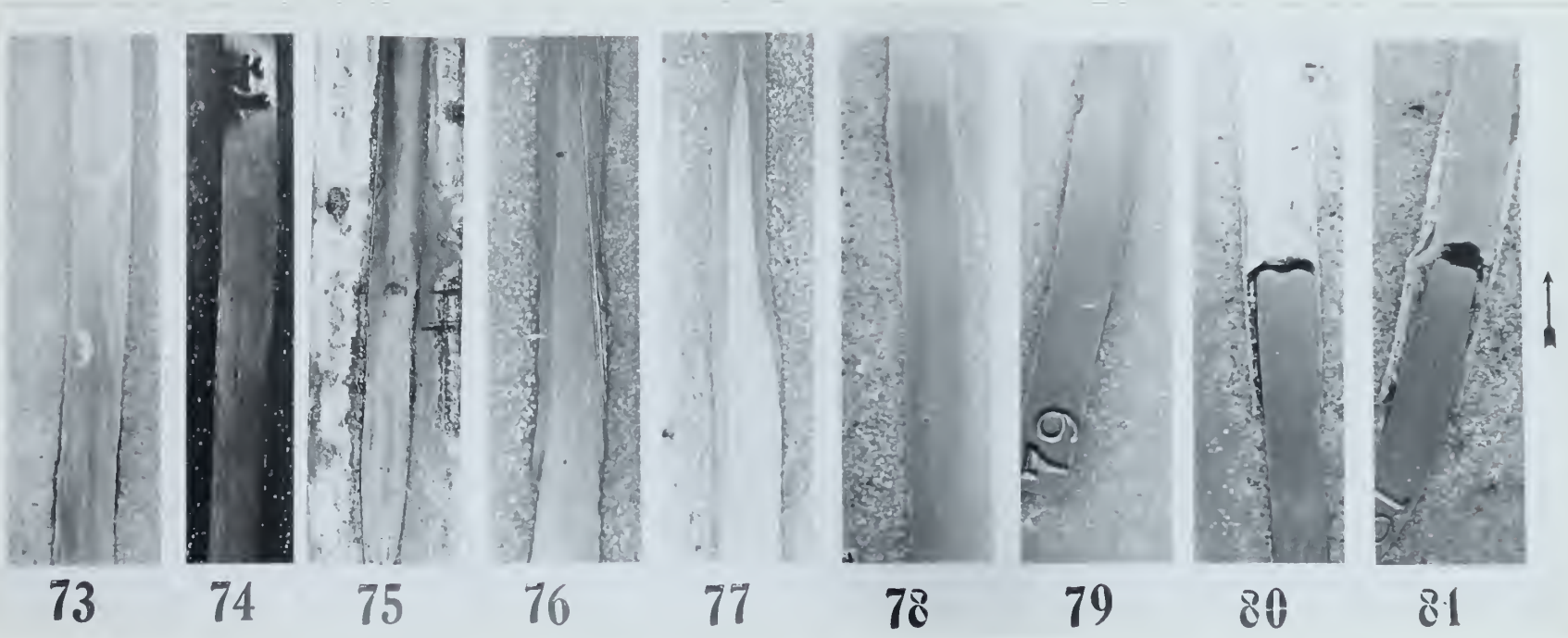


Figure A-14 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 16

Entrainment ratio = 19

Figure V-11 - Photographs of Combustion Test Bill at Mach Number Shortly Thereafter

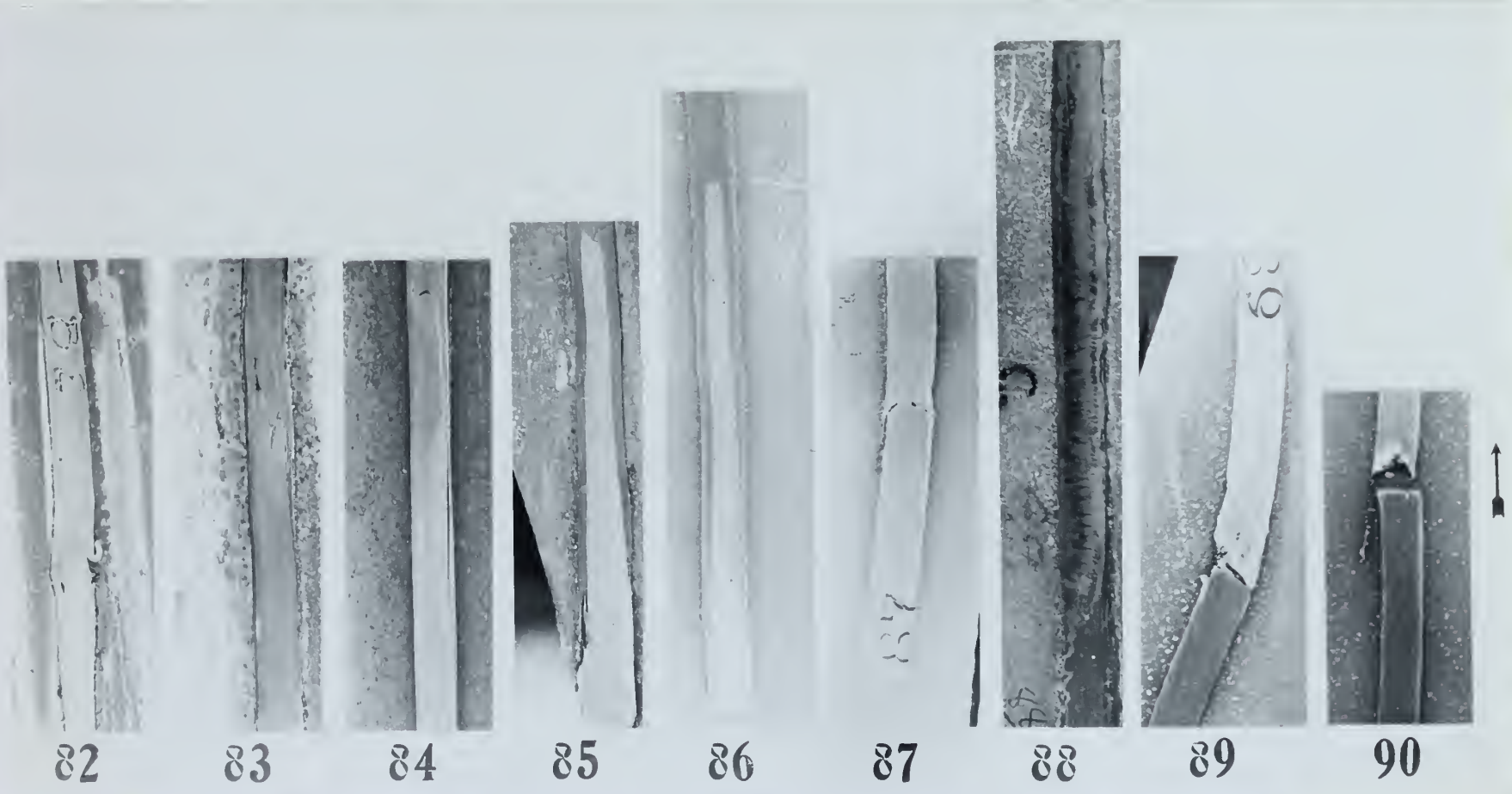


Figure A-15 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 25

Figure 4-12 - Hypothesis of Sediments Not Stirred Above Solute Injection.

Equation Used = S2

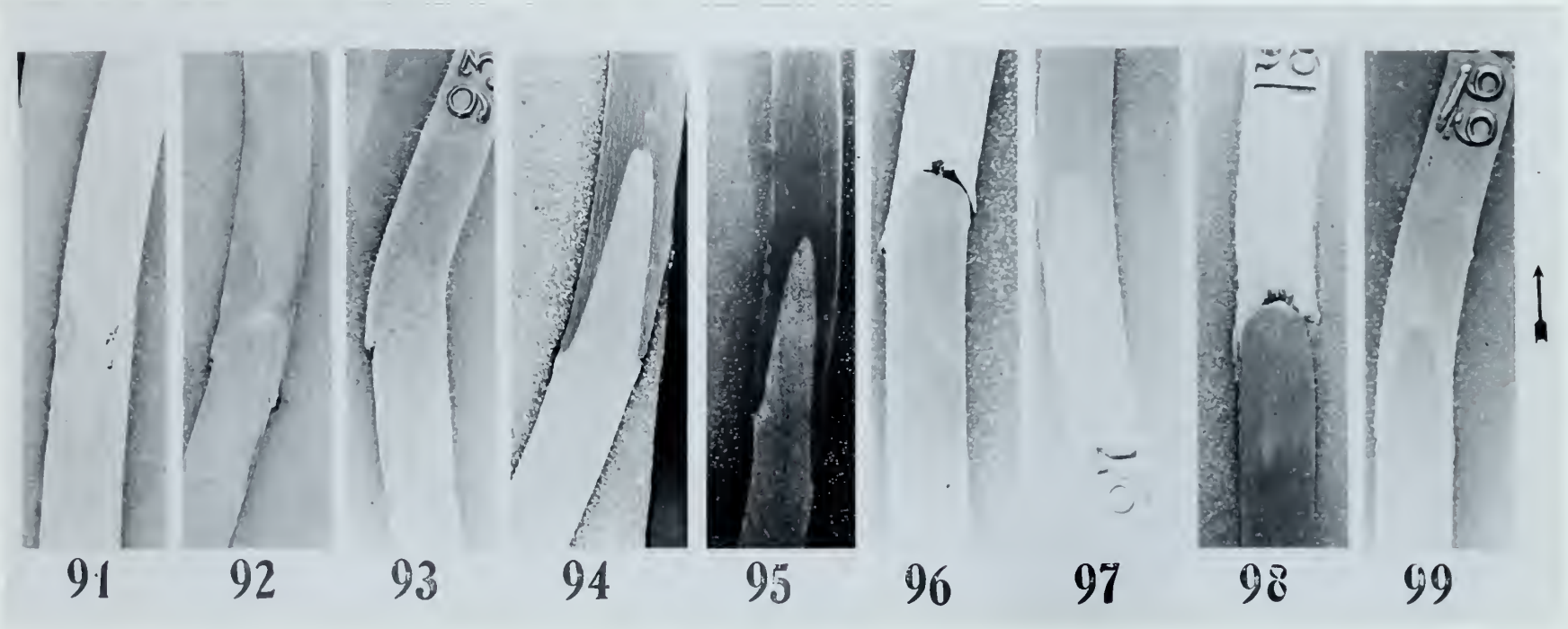


Figure A-16 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 9

Figure 4-12 - Photograph of Computer Test Bitter Weight Circuit Modules

Figure 4-13 - Photograph of Computer Test Bitter Weight Circuit Modules

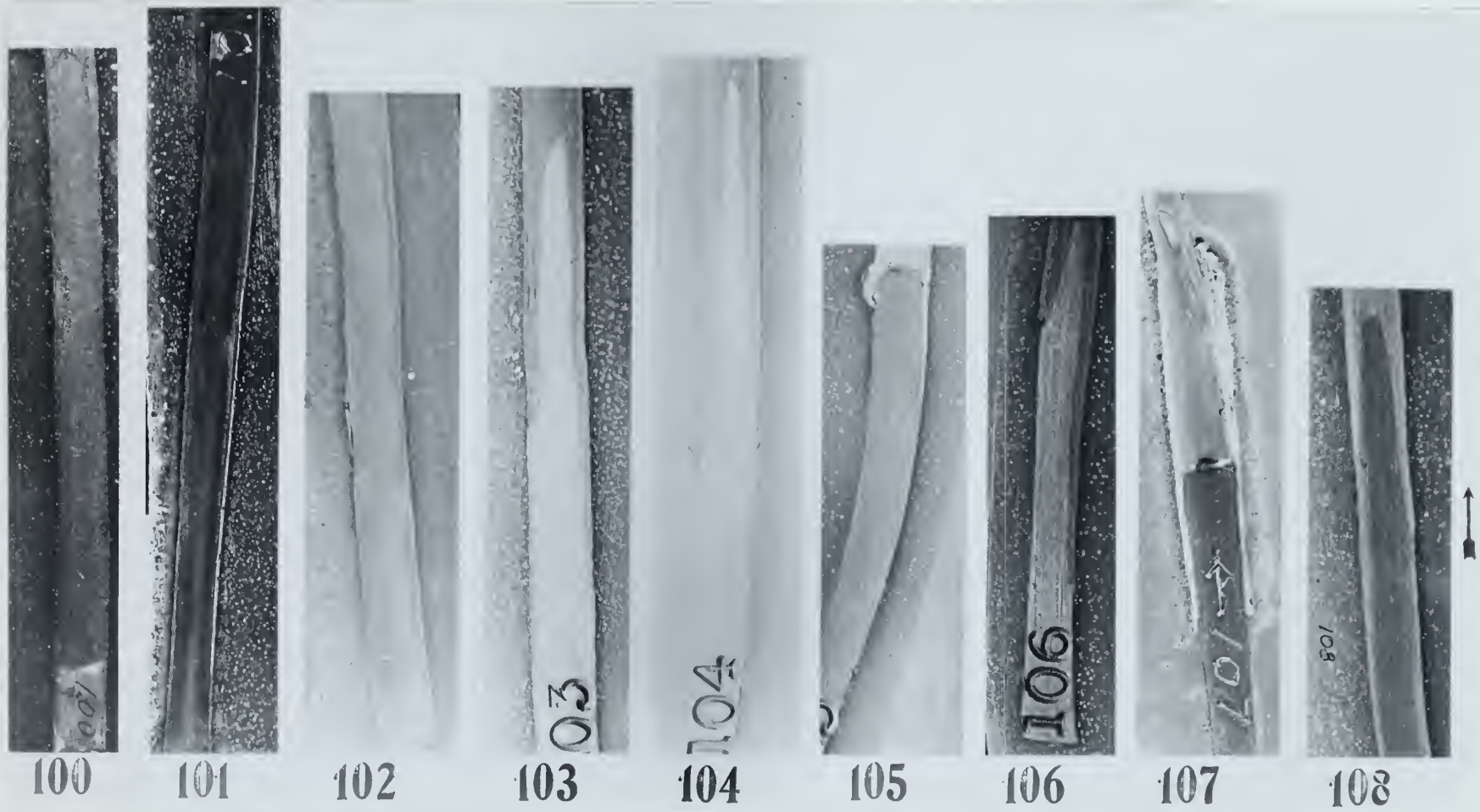


Figure A-17 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 16

Figure A-11 - Photographs of composite test specimen showing typical failure mode.

Specimen Type = IC

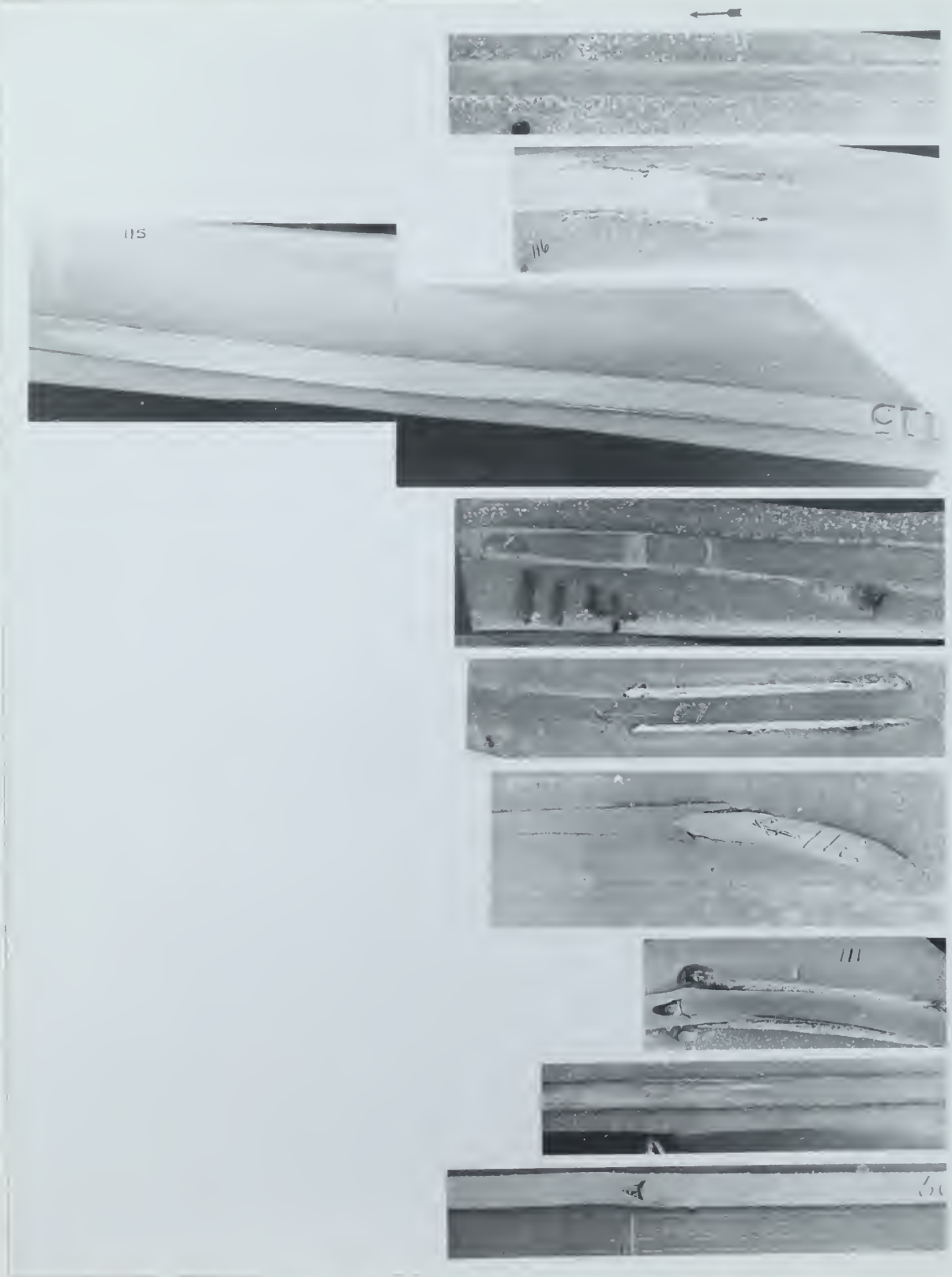


Figure A-18 - Photographs of Composite Lead Billets After Extrusion Showing Interface. Extrusion Ratio = 25

Figure A-16 - Photographs of Composite Lead Billets after Extrusion Showing Interfaces. Extrusion Ratio = 25

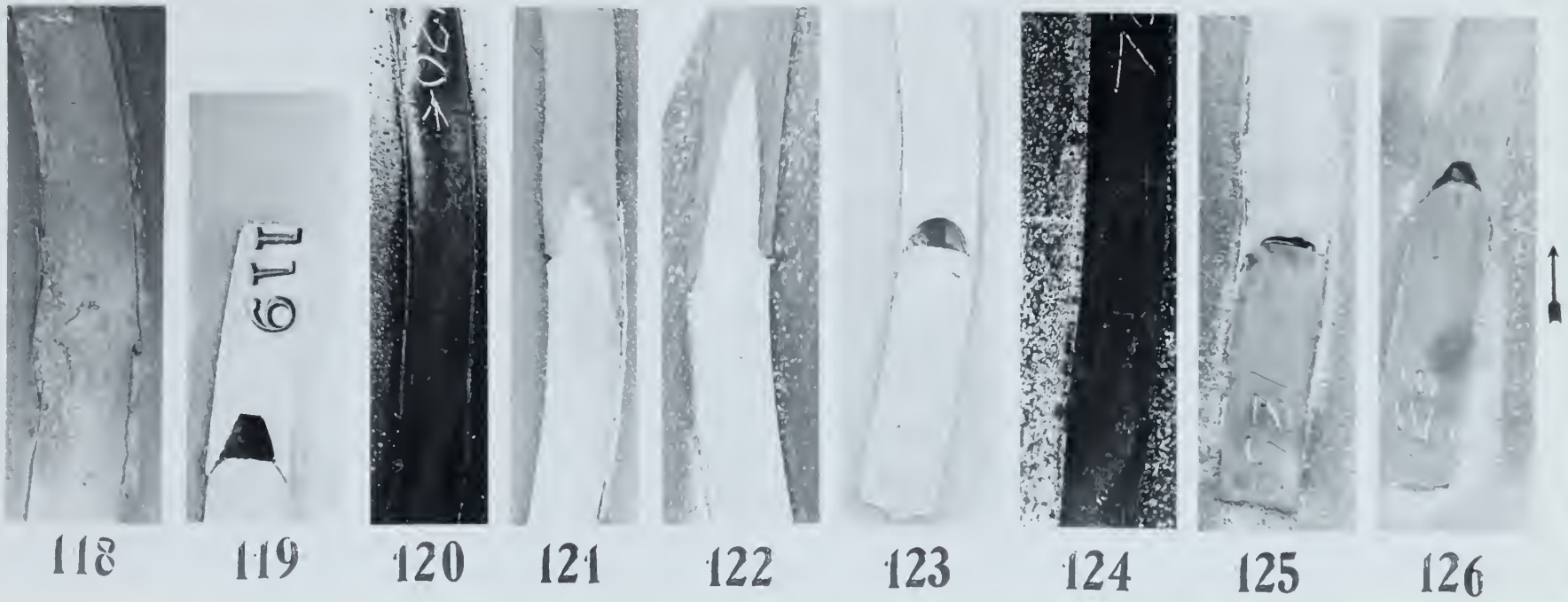


Figure A-19 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 9

Figure V-13 - Hypothetical Relationship between Satellite Data Rate and Ground Station Antenna Diameter

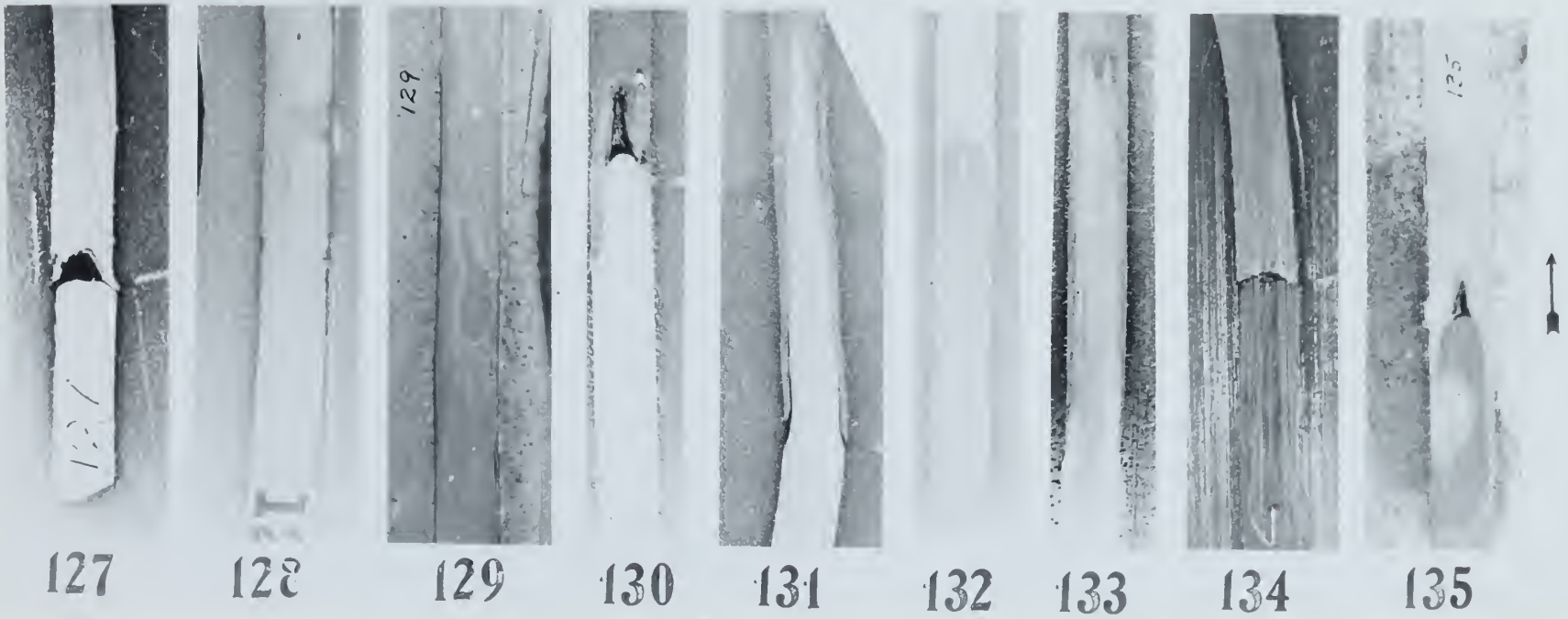


Figure A-20 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 16

Fig. 3.3 - Diagramme de combustion pour divers excès d'air

Extension ratio = 20

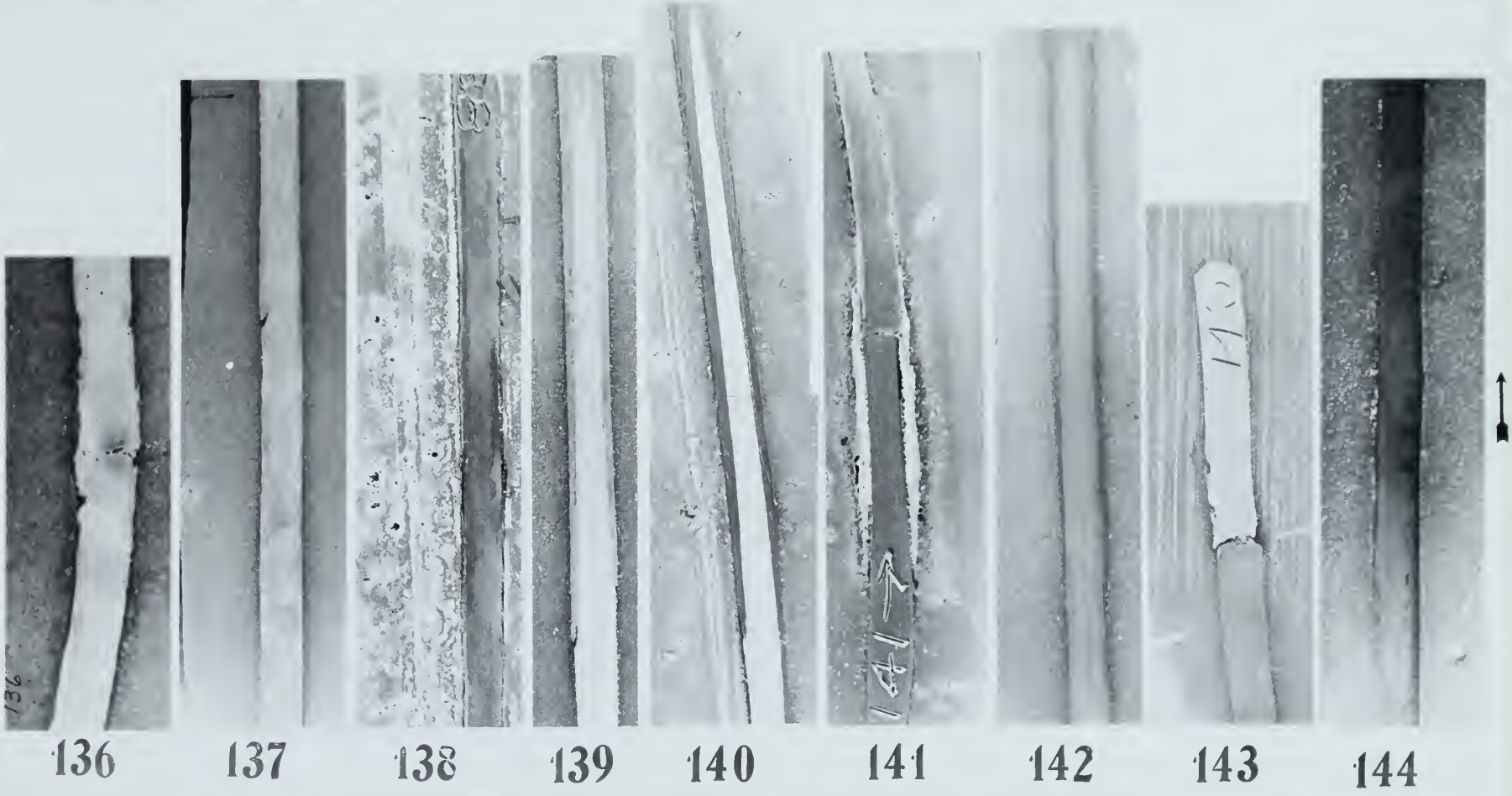


Figure A-21 - Photographs of Composite Lead Billets After Extrusion Showing Interface.
Extrusion Ratio = 25

EXPANSION RATIO = 52

Figure A-51 - Photographs of combustion test Nitrogen Tetroxide/Aerozine 50 Propellant Rocket Engine Operating at Sea Level

APPENDIX B

PLASTICINE EXPERIMENTS

1. The Material Used

The Plasticine used was a plastic clay distributed under the trade name of "Plastalena", manufactured by the Stewart Clay Company of New York 13, New York. It was a non-hardening clay which came in a variety of colors and, much to the chagrin of the investigator, a variety of hardnesses. The color appeared to have a remarkable effect on the hardness, probably because in its manufacture, a batch consisted of one color. In conversation with the manufacturer, it was learned that precise methods were not used to any degree at all.

2. Lubrication

An attempt was made to determine the best lubricant for obtaining the least friction between the clay and a bright metal surface. The following substances were tried:

a. Talc

b. Dow Corning 703 Silicone Fluid

c. Dow Corning 9981 LT

d. Shell #140 Gear Box Oil

e. Teresso #65 Hydraulic Oil

f. Mineral Oil

g. Aquadag

h. Johnson #150 Wax Draw

i. Welsh Duo-seal Oil

j. Dumore Cool Bearing Oil

k. Lubriko Grease (Density M6)

APPENDIX B

PLASTICINE EXPERIMENTS

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a. Talc
b. Dow Corning 703 Silicone Fluid
c. Dow Corning 200A DT
d. Shell Alfo Deer Dex Oil
e. Torsess 65 Hydraulic Oil
f. Mineral Oil
g. Aquadag
h. Johnson #150 Wax Drew
i. Nolah Duo-seal Oil
j. Dumore Cool Bearing Oil
k. Lubriko Grease (Density M3)

l. Liquid Green Soap

m. Water

n. Ethyl Ricinoleate (Eastman Kodak)

o. Polyethylene Glycol "600"

The test consisted of extruding Plasticine through a circular die using an extrusion ratio of 4 and a billet diameter of .750-inch. The die, cylinder wall, ram, and billet were coated with the specified lubricant and the extrusion pressure was recorded. Without going into great details of the analysis, it was found that water was the best lubricant of all the materials tried. Most of the oils showed little if any variation. The Johnson Draw Wax closely approached the water value. In no cases was it possible to lubricate the throat of the die for more than a small portion of the extrusion, which indicated that the clay was soft enough to prevent the thin film lubricant from passing into the die. This was significant in that during the initial stage of extrusion the throat was lubricated; whereas, for most of the extrusion the throat had no lubricant whatsoever. This point should be remembered in analyzing the results of extrusion with very soft materials.

One point in favor of using plain water as a lubricant was that it was not a solvent for the binder in the clay.

3. Density Measurements

Some thought was given to kneading the clay in order to insure homogeneity. Invariably kneading resulted in lower extrusion pressures. Density measurements were made on different colors and with kneaded and unkneaded clay. As suspected, density varied with color but only from a batch-wise point of view. Significant, however, was the fact that the

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m. Water

n. Ethyl Stearolate (Eastman Kodak)

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unkneaded clay was always less dense, which can be attributed to the air bubbles existing in the clay prior to kneading. This variation amounted to about 1 percent.

4. Interface Study

A series of simple extrusions were conducted using two different colored Plasticines in order to study the formation of the interface which developed. No quantitative data was taken, since the object was to determine the feasibility of using the Plasticine as an extrusion medium. It was from these experiments that it was decided to use a metal such as lead. The main reason for its unacceptability was the lack of reproducibility and the difficulty experienced in obtaining accurate measurements.

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b. Interface Study

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APPENDIX C

DOUBLE EXTRUSION EXPERIMENT WITH ALUMINUM

In order to determine if the results obtained in the double extrusion experiment using Plasticine were applicable only to that material alone, the same basic experiment was carried out using aluminum.

A billet, shown in Figure C-1, was machined from 145 aluminum. A 1/8-inch hole was drilled as indicated and filled with powdered copper so that a radiograph could be taken in order to show the results of the extrusion on a transverse grid line. This billet was then heated to 400°C and extruded through a 1.054-inch die, giving an extrusion ratio of 4. Figure C-2 is the radiograph of the billet after the first extrusion. This billet was then re-extruded from the opposite direction, using a .55-inch die which gave an extrusion ratio again of 4. Figure C-3 is the radiograph of this final extrusion.

Note that the extrusion defect after the first extrusion is quite normal and is what one would expect; however in Figure C-3 the extrusion defect has not reversed itself anywhere along the line and has greatly increased in length. This inability of the defect to show even small signs of reversing itself indicates that this is an instance where the defect after the first extrusion was too great, and in fact, far exceeded the point at which it could be reversed.

It would be interesting to repeat this experiment and for the first extrusion use an extrusion ratio of around 1.5 and then re-extrude at about 10-16. In this way, the defect would be around the 15° cone angle range and could possibly result in a flat interface.

APPENDIX C

DOUBLE EXTRUSION EXPERIMENT WITH ALUMINUM

In order to determine if the results obtained in the double extrusion experiment using plasticine were applicable only to that material alone, the same basic experiment was carried out using aluminum.

A billet, shown in Figure C-1, was machined from 1/2 aluminum. A 1/8-inch hole was drilled as indicated and filled with powdered copper so that a radiograph could be taken in order to show the results of the extrusion on a transverse grid line. This billet was then heated to [illegible] and extruded through a 1.0[illegible]-inch die, giving an extrusion ratio of 4. Figure C-2 is the radiograph of the billet after the first extrusion. This billet was then re-extruded from the opposite direction, using a .55-inch die which gave an extrusion ratio again of 4. Figure C-3 is the radiograph of this final extrusion.

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It would be interesting to repeat this experiment and for the first extrusion use an extrusion ratio of around 1.5 and then re-extrude at about 10-16. In this way, the defect would be around the 135° cone angle range and could possibly result in a flat interface.

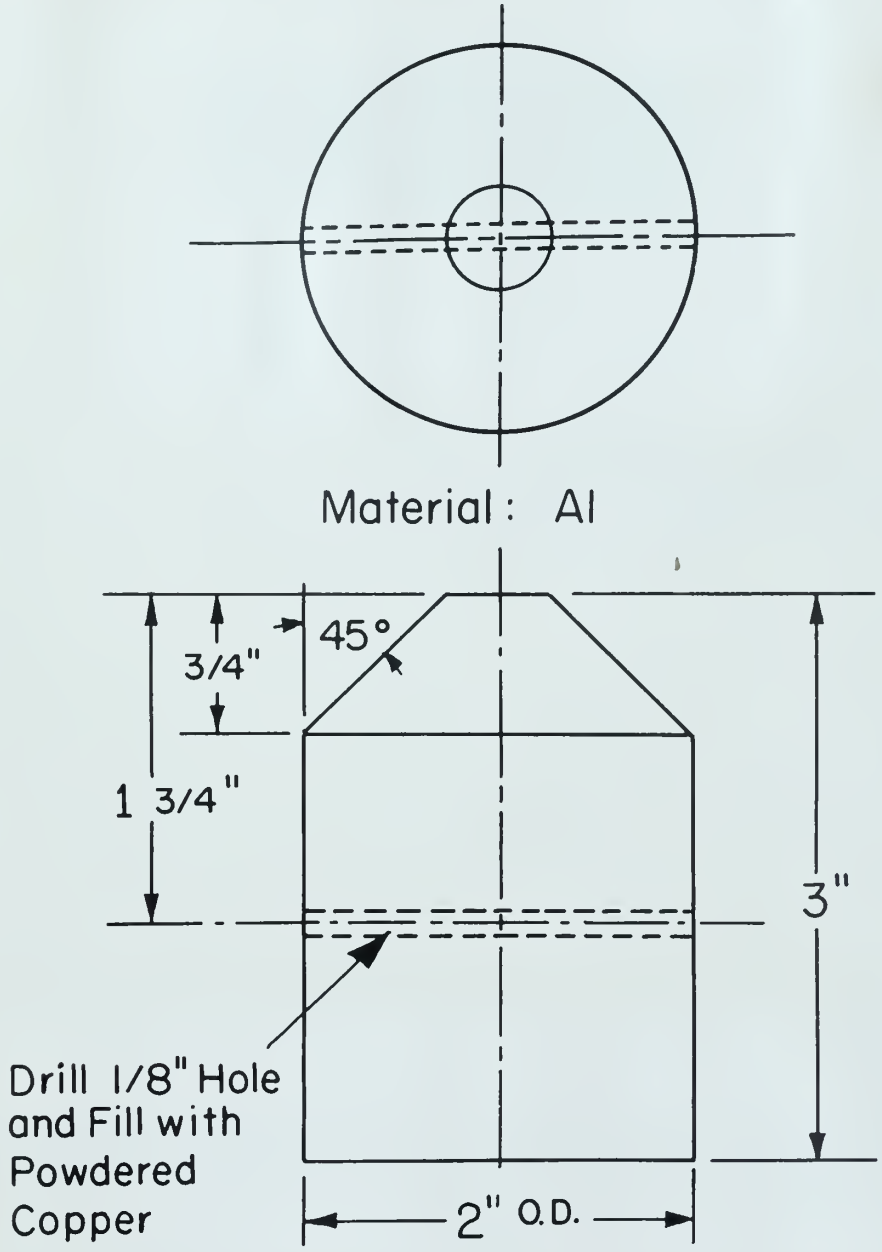

Figure C-1

Billet for Aluminum Double Extrusion

Figure C-2 - Radiograph of Aluminum Billet After First Extrusion Showing Distortion of Copper-Filled Hole. Direction of First Extrusion was from Right to Left.

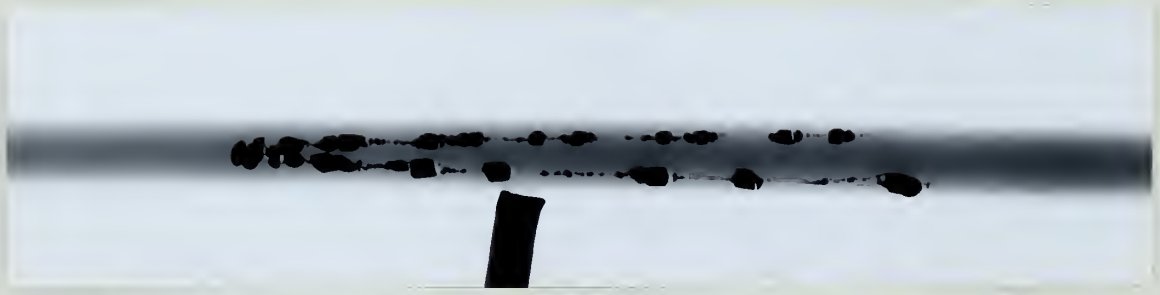

Figure C-3 - Radiograph of Aluminum Billet After Second Extrusion Showing Distortion of Copper-Filled Hole. Direction of Second Extrusion was from Left to Right.

28873

W335 Wegner
A study of metal flow during integral end closure extrusion cladding.

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A study of metal flow during integral end closure extrusion cladding.

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